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DEPARTMENT OF THE ARMY TECHNICAL MANUAL

# GEOLOGY AND ITS MILITARY APPLICATIONS

*DEPARTMENT OF THE ARMY • AUGUST 1952*

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# CONTENTS

# CHAPTER 1

# INTRODUCTION

## 1. Purpose

The purpose of this manual is to show how the science of geology can be applied to military operations. The manual is intended for intelligence and operations officers of battalion level or higher. It is to be used for both reference and training.

## 2. Scope

This manual presents information of the type a trained geologist would be able to supply for use in solving the military problems of terrain evaluation, foundations, excavations, construction materials, site selection, and water supply. The manual describes the various maps and reports useful in the geologic study of the earth. It includes a brief introduction to geologic materials, features, and processes. The manual does not cover the entire subject of geology and will not make a qualified geologist of the individual soldier.

## 3. References

Appendix I is a bibliography of publications, grouped according to the chapter to which they are related.

## 4. Definition of Geology

Geology is the science which deals with the substance, structure, and origin of the earth. It is the application of chemistry, physics, and biology, with their related sciences, to the study of the earth. The formation and alteration of rocks are the result of chemical, physical, and biological phenomena; the behavior of gases, water, and molten and solid rock on and below the surface of the earth is principally a physical phenomenon; the occurence of animal and plant remains in rocks is a biological phenomenon. Geology also overlaps such other sciences as astronomy, climatology, geography, hydrology,

oceanography, and pedology. The relationship is especially close between pedology (soil science or soil mechanics) and geology since soil is the product of the mechanical breakdown and chemical alteration of rocks and rock particles.

## 5. Geology and Military Operations

In military operations, the geologist can translate geologic information into concepts which can be used readily and effectively in conjunction with combat and engineering needs. Combat units, for example, benefit from geologic information in the evaluation of the trafficability of soils, the estimation of the fordability of streams, and the availability of concealment and cover. Engineering units would use geologic information in the location and use of construction materials, the location of ground-water supplies, the siting of roads and airfields, the evaluation of the suitability of foundations, the proper location of excavations, and evaluation of possible sites for underground installations.

## 6. Geology and Military Planning

Military commanders should incorporate geologic information with other pertinent data when planning military operations. Since it is impossible to predict its ultimate military value, available geologic information should be included as standing operating procedure. During operations, the actual geologic conditions encountered should be continuously observed to verify or modify the preliminary estimate. Information so obtained may have an important bearing on adjacent or future projects.

# CHAPTER 2

# BASIC PRINCIPLES OF GEOLOGY

## Section I. MATERIALS OF THE EARTH'S CRUST

### 7. General

The crust of the earth, generally regarded as a layer 30 to 50 miles thick, is composed of a variety of solid materials. The most common and widespread of these solids is a substance known as rock. Rock is composed of numerous natural compounds called minerals, and is concealed to a large extent by a thin veneer of loose material called soil by the engineer. This section defines and describes these materials and presents those physical properties which are most important to the military engineer.

### 8. Minerals

Minerals are naturally occuring inorganic elements or compounds possessing a typical chemical composition and, in most, a definite atomic arrangement. Those minerals which do not possess a definite atomic arrangement are referred to as being *amorphous* as, for example, the mineral opal.

### 9. Mineral Identification

The physical properties characteristic of a mineral, controlled by its chemical composition and atomic structure, are valuable aids in its rapid field identification. Those characteristics which can be determined by simple field tests are introduced to aid in the identification of minerals, and indirectly in the identification of rocks.

*a. Hardness.*

(1) The *hardness* of a mineral is a measure of its ability to resist abrasion or scratching. A simple scale, based on empirical tests for hardness, has been universally accepted. The 10 minerals selected to form the standard of comparison, listed in order of increasing hardness from 1 to 10, are:

| | |
|---|---|
| Talc or mica | 1 |
| Gypsum (fingernail about 2) | 2 |
| Calcite | 3 |
| Fluorite (copper coin between 3 and 4) | 4 |
| Apatite (knife blade about 5) | 5 |
| Feldspar (window glass about 5.5) | 6 |
| Quartz | 7 |
| Topaz or beryl | 8 |
| Corundum | 9 |
| Diamond | 10 |

(2) In testing the hardness of a mineral, always use a fresh surface; always rub the mark to make sure it is really a groove made by scratching. If an unknown mineral scratches and in turn is scratched by a member of the scale or a testing medium (copper coin, pocket knife, or window glass), they are of equal hardness.

*b. Cleavage.*

(1) A mineral is said to have *cleavage*, if smooth plane surfaces are produced when the mineral is broken. This is a fairly consistent physical property of minerals, and when present is of great value in their identification.

(2) Cleavage invariably occurs along parallel planes. Some minerals have one cleavage; others have two, three, or even more different cleavage directions which may have varying degrees of eminence. The number of cleavage directions and the angle at which they intersect serve as an aid in the identification of a mineral (fig. 1).

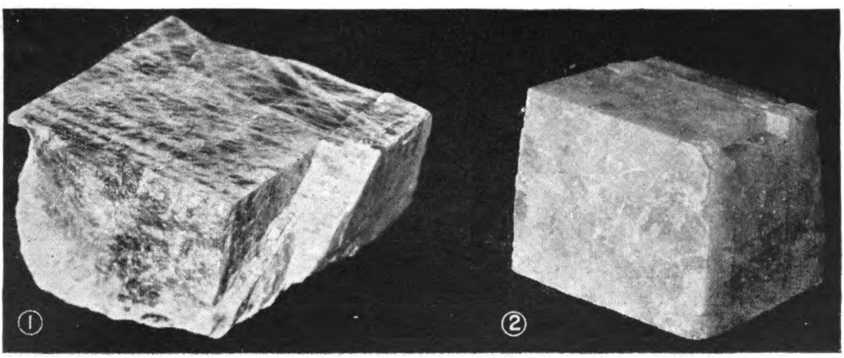



***Figure 1. Mineral cleavage.***

*c. Fracture.*

(1) The broken surface of a mineral which does not exhibit cleavage planes has what is called *fracture.* In some cases, this property may be very helpful in field identification.

(2) The common types of fracture are: *conchoidal,* if the fracture has concentric curved surfaces like the inside of a clam shell; *irregular,* if the surface is rough; and *splintery,* if it has the appearance of wood.

*d. Luster.*

(1) The luster of a mineral is the appearance of its surface due to the quality and intensity of the light reflected. Two major kinds are recognized, *metallic* and *nonmetallic.* The main difference between the two is indicated by the names. In addition, metallic minerals are opaque or nearly so, whereas nonmetallic minerals are transparent on their thin edges.

(2) Some of the common nonmetallic lusters are *vitreous,* having the luster of glass; *pearly,* having the irridescence of pearl; and *adamantine,* having brilliant luster like that of a diamond.

*e. Color.* The color of a mineral, as an aid in its identification, must be used with proper precaution, since some show a wide range without perceptable change in composition. On the whole, however, color is fairly consistent, particularly in the metallic minerals where it is a great help in field identification.

*f. Streak.* The color of the fine powder of a mineral, obtained by rubbing it on some white substance, preferably unglazed porcelain, is known as its *streak.* The streak of a mineral is quite consistent within a given range even though its color may vary.

## 10. Common Rock-Forming Minerals

Although approximately 2000 varieties of minerals are known, about 200 have definite geologic and economic importance. Of these 200, only a dozen or so are found in most common rocks. Following are descriptions of the most important of these rock-forming minerals or mineral groups.

*a. Quartz.* Silicon dioxide. Hardness 7, scratches glass easily. No cleavage. Fracture conchoidal. Luster vitreous. Common varieties usually white or colorless. Streak white or colorless. Typical examples are *milky quartz* and *rock crystal quartz.*

*b. Feldspar Group.* Potassium-aluminum silicates or sodium-calcium-

aluminum silicates. Hardness 6, scratches glass with difficulty. Luster vitreous. Streak white. *Orthoclase* is a common potassium rich variety which is typically colorless, white, gray, pink, or red, and has two good directions of cleavage that intersect at 90° to each other (① of fig. 1). The sodium-calcium-rich feldspars, commonly referred to as *plagioclase feldspar,* are typically of various shades of gray, have two cleavage directions that intersect at angles of nearly 90° to each other, and can be distinguished from orthoclase feldspar by the presence of fine, parallel lines that appear on the basal cleavage surface.

*c. Mica Group.* Complex potassium-aluminum silicates, often with magnesium, iron, and sodium. Hardness 2 to 3, can be scratched with the thumbnail. Perfect cleavage in one direction. Luster vitreous to pearly. Transparent with varying shades of yellow, brown, green, red, and black in thicker specimens. Streak white. The chief characteristic of this group is that its minerals are capable of being split very easily into extremely thin and flexible sheets. *Biotite* (black) and *muscovite* (white) are two representative varieties.

*d. Amphibole Group.* Complex calcium-magnesium-iron silicates. Hardness 5 to 6. Cleavage in two directions at angles of 56° and 124°. Color light to dark green to black. Streak white to grayish-green. *Hornblende* is a common variety that is usually distinguishable from other amphiboles by its dark color.

*e. Pyroxene Group.* Complex calcium-magnesium-iron silicates, closely analogous chemically to the amphibole group. Hardness 5 to 6. Two directions of cleavage making angles of about 87° and 93°, an important characteristic useful in distinguishing between the minerals of the pyroxene and amphibole groups. Color light to dark green to black. Streak white to grayish green. *Augite* is a common variety that can be distinguished from hornblende by its cleavage angles.

*f. Olivine.* Magnesium-iron silicate. Hardness 6.5 to 7. No cleavage. Luster vitreous. Color olive to grayish-green to brown. Streak white to colorless. An important characteristic of this mineral, due to its granular texture, is its *friability* or tendency to crumble into small grains.

*g. Calcite and Dolomite.* Calcium carbonate and calcium magnesium carbonate. Hardness 3 and 3.5 to 4. Perfect cleavage in three directions (② of fig. 1). Luster vitreous to pearly. Usually white or colorless but may appear in shades of gray, red, green, blue, or yellow. Streak white. Calcite usually is crystalline, whereas dolomite is commonly found in coarse, granular masses.

*h. Clay Minerals.* Extremely complex hydrous aluminum silicates. Hardness 2 to 2.5. Luster dull to earthy. Color white, gray, greenish, and yellowish-white. There are three important groups of clay minerals, namely, *kaolinite, montmorillonite,* and *illite.* These three groups have much the same characteristics. Almost all clays contain one or more of these three groups. These clay minerals can only be distinguished under the microscope and with the aid of X-ray equipment. They occur typically in very fine grains and masses of thin micalike scales.

*i. Limonite and Hematite.* Hydrous ferric oxide and ferric oxide. Hardness 5.5 and 6.5. No cleavage. Color dark brown to black and reddish-brown to black, depending on the variety. Limonite has a yellowish-brown streak and is characteristically found in dark-brown, nodular, earthy masses with no apparent crystal structure whatsoever. Hematite has a light to dark Indian-red streak; usually occurs in earthy masses, but occasionally in botryoidal or reniform shapes known as *kidney ore,* and in foliated masses known as *specular iron.* Limonite and hematite are important coloring and cementing minerals in many different rocks especially the sedimentary group.

## 11. Rocks

*a. Definition.* In a broad sense, rocks are aggregates of minerals. The principal exceptions to this definition are the products of organic decay, such as coal, and volcanic glasses, such as obsidian. To the engineer, the term rock signifies firm and coherent or consolidated substances that cannot normally be excavated by manual methods alone. To the geologist, the term rock includes not only the consolidated materials of the earth's crust but also the unconsolidated and uncemented materials, such as clay, sand, and gravel. In this manual, the engineer's definition will be used.

*b. Major Types.* Based on the principal mode of origin, rocks are grouped into three large classes: igneous, sedimentary, and metamorphic. These are discussed in detail in paragraphs 12, 13, and 14.

*c. Distribution of the Major Types.*

(1) Igneous and metamorphic rocks are closely associated in distribution (fig. 2). Although they underlie all parts of the world, in large parts of the land area they are deeply buried beneath sedimentary rocks. Igneous and metamorphic rocks reach the surface in mountains and in some lower areas

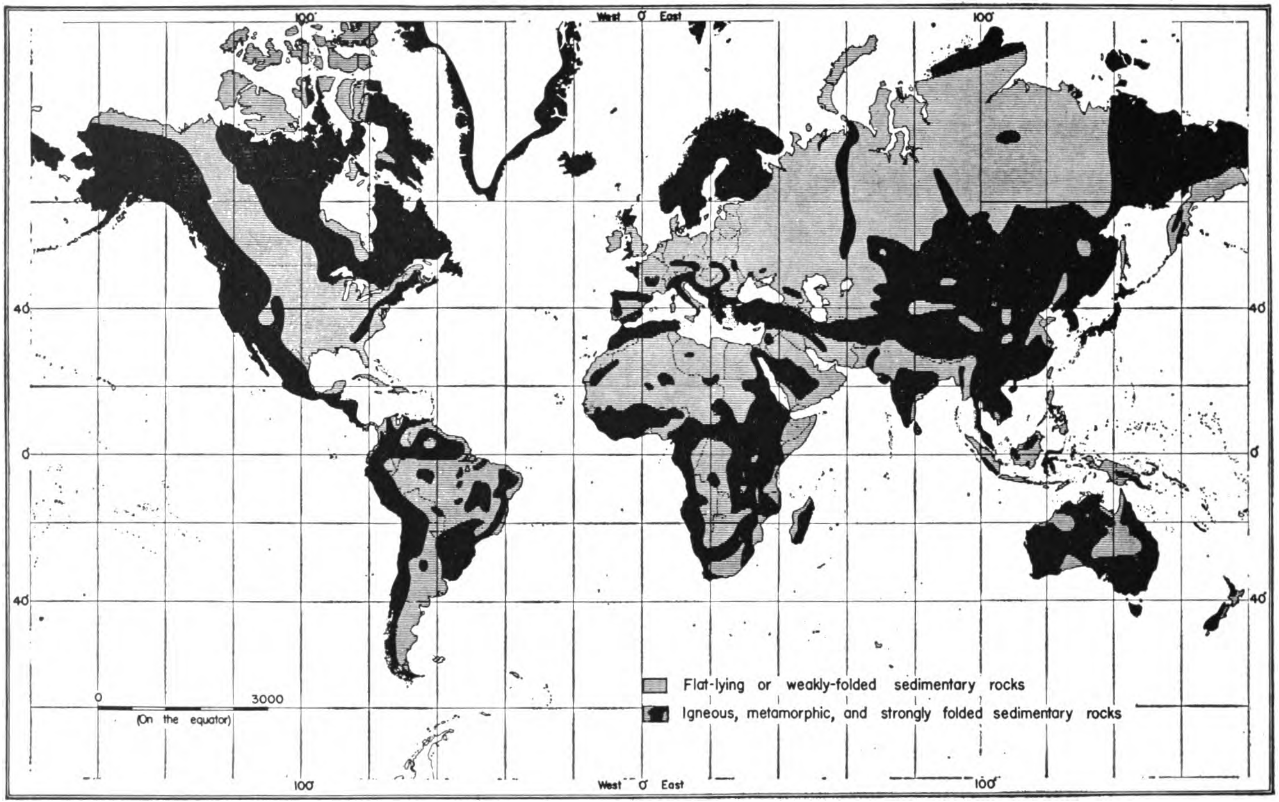



*Figure 2. World-wide distribution of major rock types.*

that represent worn-down ancient mountains. Some of these areas, called *shields,* form large parts of each continent: eastern Canada, eastern South America, northern Europe, central Siberia, western Australia, and southern and eastern Africa.

(2) Sedimentary rocks, essentially flat lying, underlie a thick mantle of unconsolidated material in the largest valleys and coastal plains and interior basins; occur as horizontal beds in most of the great plateaus of the world; and occur in mountains, commonly along the flanks, in tilted and folded positions. The above relationships are shown in a very generalized way by figure 2.

(3) Lava flows, along with sedimentary rocks, form the great plateaus of the world (fig. 124).

## 12. Igneous Rocks

*a. Definition.* The *igneous rocks* are commonly referred to as primary rocks. They are those rocks which have solidified from a molten mass called *magma,* when in the body of the earth, or *lava,* when extruded on the earth's surface. Igneous rocks owe their variations in significant characteristics to differences in the chemical composition of the original molten mass and the physical conditions under which the molten mass solidified.

*b. Mode of Origin.* At times and in various locations, molten rock is forced upward from some unknown depth beneath the earth's surface. This material, which cuts through or intrudes the overlying rock, may stop below the surface where it is cooled and solidified or it may reach the surface. These two principal ways in which rocks are formed have led to the concept of the two-fold division of igneous rock masses: *intrusive,* those that have formed at depth below the earth's surface, and *extrusive,* those that have solidified on the surface. These rock masses are further classified according to their shape or form and their relationship to the structure of the intruded rock as follows:

(1) *Intrusive igneous rock masses* (fig. 3).

(*a*) *Dikes and sills. Dikes* are tabular igneous bodies that are commonly intruded at an angle to the bedding of the surrounding formations (fig. 4). *Sills* are similar bodies which are usually intruded parallel to the bedding planes of the rocks which inclose them. The thickness of a dike or sill may vary from a few inches to many yards, but this dimen-

sion is usually quite small in relation to the length and width of the intrusive body. For example, the Palisades sill of New York which has a thickness of 1000 feet has a length of over 100 miles.

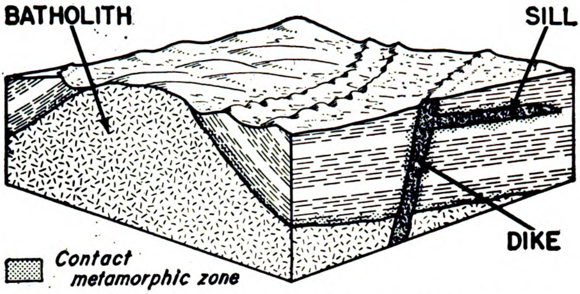



*Figure 3. Intrusive igneous masses.*

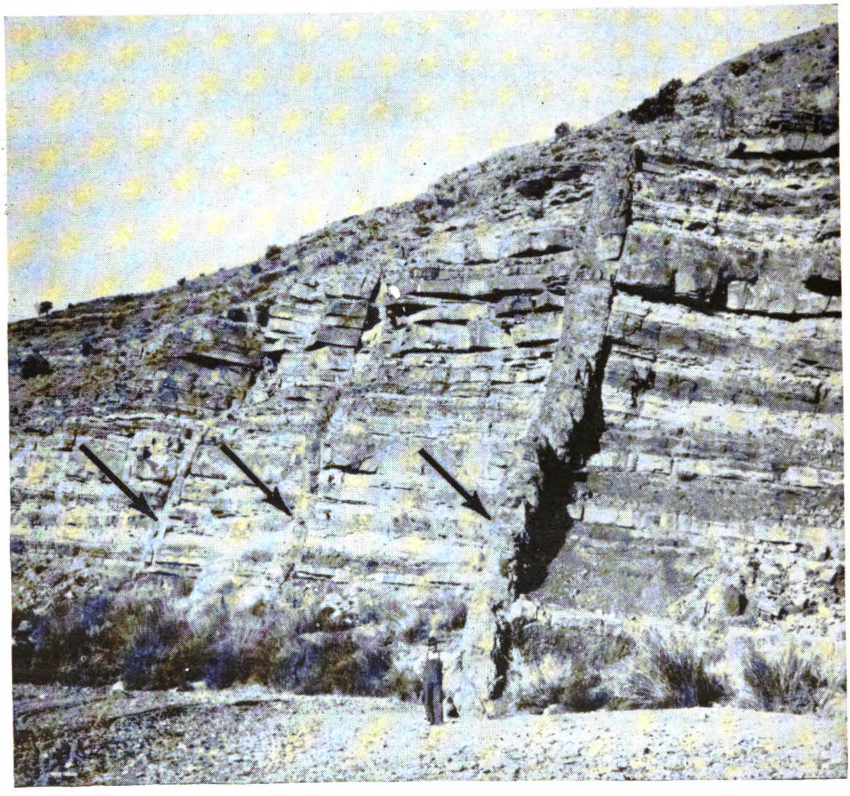


***Figure 4. Three dikes cutting sedimentary beds.***

(*b*) *Batholiths.* Very large, irregular masses of intrusive igneous rock, defined as covering an area of over 40 square miles, are called *batholiths.* Though originally deeply buried beneath the earth's surface, they have become exposed through processes of uplift and erosion (fig. 5). A very striking example of an exposed batholith is the one in central Idaho which has an estimated area of over 80,000 square miles.

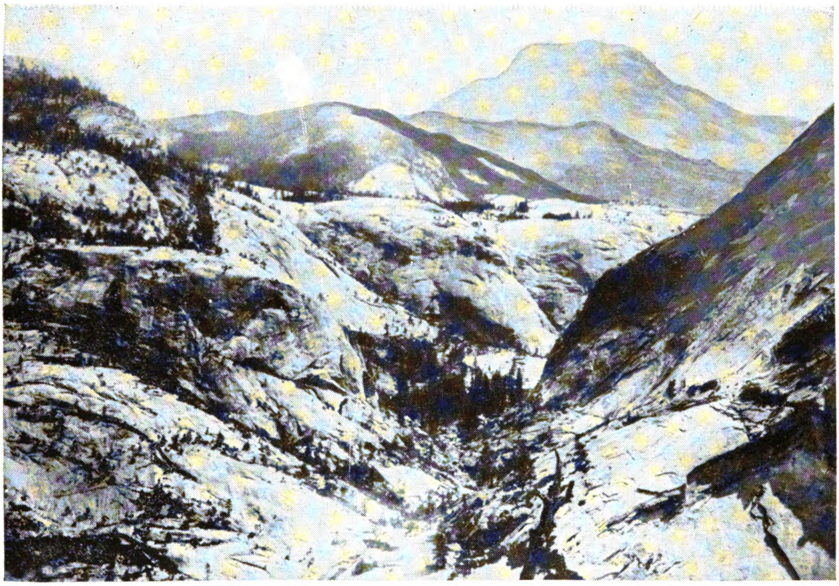


*Figure 5. Eroded surface of the Sierra Nevada Batholith.*

(2) *Extrusive igneous rock masses.*

(*a*) *Lava flows. Lava flows* are the result of the solidification of lava which has issued from fissures in the earth's crust or poured out of volcanoes. These flows are the most common modes of occurrence of extrusive igneous rocks (figs. 6 and 7). Among the most notable of the enormous lava flows in the world is the Deccan region of western India and the Columbia River Plateau of Washington, Oregon, and Idaho. This phenomenon is discussed in greater detail in paragraph 43.

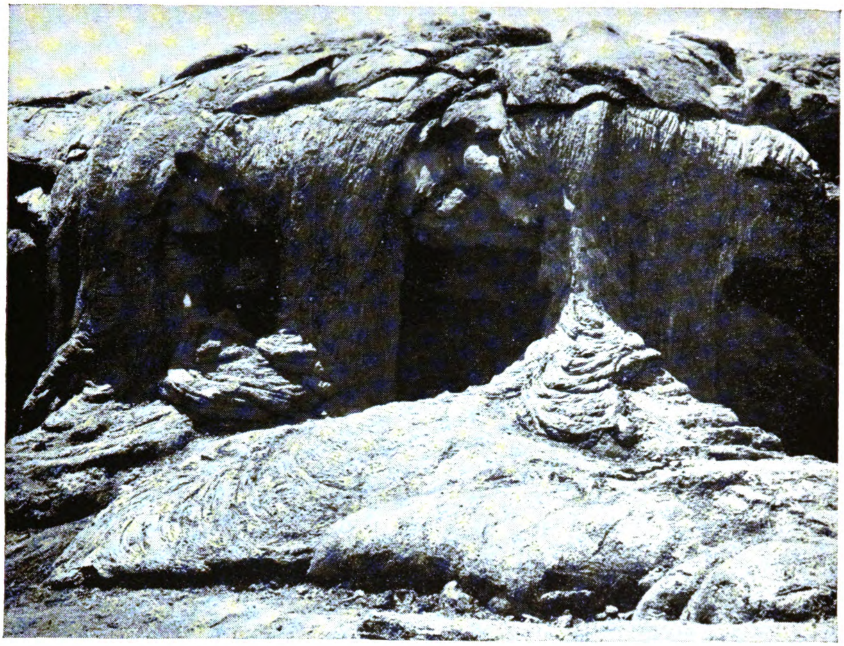


*Figure 6. Solidified lava flow, ropy type. Kilauea, Hawaii National Park.*

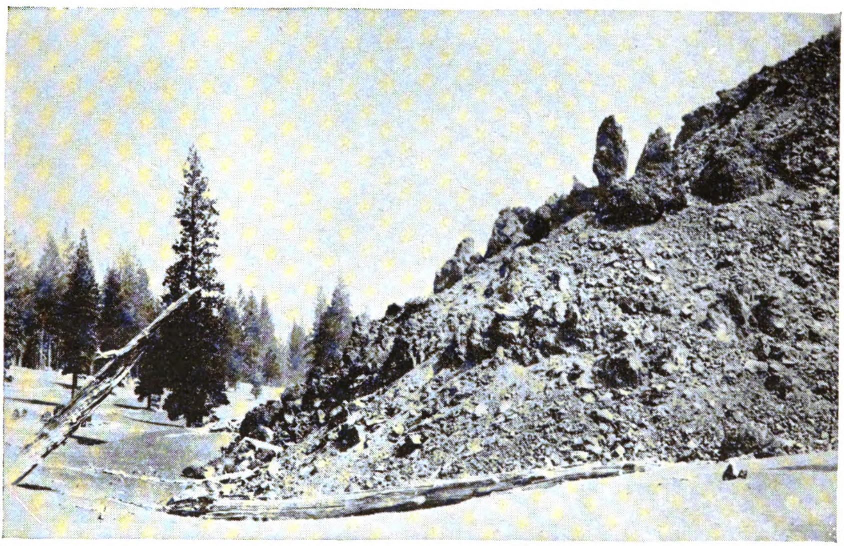


*Figure 7. Solidified lava flow, blocky type. Lassen Peak, California. Layer of volcanic ejecta (ash) covers area at left and in foreground.*

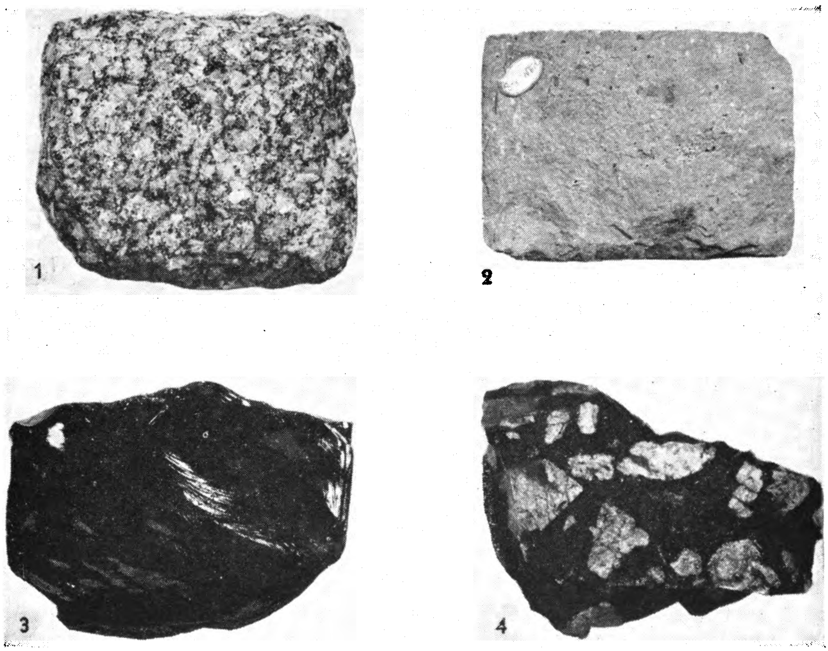
(b) *Pyroclastics.* Explosive volcanoes frequently eject great quantities of broken and pulverized rock material and blobs of molten lava which solidify before striking the ground. These solid volcanic ejecta are termed *pyroclastic material* which varies in size from great *blocks* weighing many tons, through small *cinders* or *lapilli* to fine dust size particles referred to as *ash* (fig. 7).

c. *Conditions Influencing Composition.*

(1) A mass of molten rock material may be regarded as a complex solution containing many radicles, one of which behaves as an acid (oxide of silicon) and numerous others which behave as bases (oxides of iron, aluminum, calcium, magnesium, potassium, and sodium). As the molten mass gradually solidifies, minerals separate out of solution. If more silica is available than is necessary to satisfy the bases in the magma, the surplus will show itself as free silicon dioxide (quartz), and the resulting rock is said to be *acidic.* If the bases are excessive, the mineral composition will reveal this condition by the presence of iron-magnesium minerals, and the rock is said to be *basic.*

(2) As a rule, acidic rocks are light-colored; basic rocks are dark to black. The one striking exception to this rule is obsidian, an acid rock which is normally black.

d. *Conditions Influencing Texture. Texture* refers to the size and arrangement of the mineral grains in a rock (fig. 8). These factors as applied to igneous rocks are influenced, primarily, by the rate at which the molten mass, magma or lava, cools. The cooling, in turn, is directly controlled by the size and shape of the mass and the position in or on the earth's crust where the mass solidifies. A constant rate of cooling produces an *equigranular texture;* that is, rocks in which the constituent mineral grains are approximately the same size. In general, the slower the molten material cools, the larger the size of the mineral grains. A change in the rate of cooling from an initial slow phase followed by a more rapid phase usually produces an *inequigranular* or *porphyritic texture* (④ of fig. 8); that is, rocks in which the mineral grains are of two dominant size groups: *phenocrysts* or large grains in a *groundmass* or background of smaller grains. Textural terms used in the classification of igneous rocks are discussed in (1) through (3) below. The grain sizes refer to the general, overall appearance of equigranular rocks and to the groundmass of porphyritic rocks.



1. Coarse-grained
2. Fine-grained
3. Glassy
4. Porphyritic

*Figure 8. Textures of igneous rocks.*

(1) *Coarse-grained.* When solidification of the molten rock takes place under a thick cover of rock as, for example, in a batholith, large crystals are formed. They are visible to the unaided eye. The resultant rock texture is referred to as coarse-grained (① of fig. 8).

(2) *Fine-grained.* When molten rock is injected into the upper layers of the crust, such as in sills and in dikes, solidification takes place much more rapidly, especially when the molten masses are relatively thin. Under these conditions, crystals of like or equal size generally form throughout the whole mass of rock but the grain size is much smaller. This is the *fine-grained* texture in which the individual grains can generally be seen only with a strong hand lens or with a microscope (② of fig. 8).

(3) *Glassy* (*noncrystalline*). When the molten material is forced to the earth's surface, as in volcanic eruptions and along

fissure flows, solidification is rapid and the resultant rock has a *noncrystalline* or *glassy texture* (③ of fig. 8).

*e. Classification of Igneous Rocks.* Table I lists the common igneous rocks. Those of similar chemical composition or mineral content are listed in the vertical columns; those of similar textures are listed in the horizontal columns. Classification of each variety is dependent on both texture and chemical composition.

*Table I. Common igneous rocks.*

| Texture | Composition | | |
|---|---|---|---|
| | Acidic rocks (more than 50 percent silica) | | Basic rocks (less than 50 percent silica) |
| | Light-colored minerals, chiefly feldspar, predominate | | Dark-colored minerals predominate |
| | Abundant quartz | Little or no quartz | Abundant amphibole, pyroxene, and plagioclase feldspar |
| Coarse-grained (mineral crystals easily visible to naked eye). | Granite | Diorite | Gabbro. |
| Fine-grained (mineral crystals generally invisible to naked eye). | Rhyolite | Andesite * | Basalt *. |
| Glassy | Obsidian, pitchstone, pumice. | | |

*Sometimes called traprock.

*f. Minerals in Common Igneous Rocks.*

(1) *Granite* and *rhyolite* are composed largely of quartz and feldspar (mainly the orthoclase variety) and, as a rule, contain mica (generally the biotite variety).

(2) *Diorite* and *andesite* are composed of feldspar (mainly plagioclase varieties) and one or more dark minerals (biotite, hornblende, or pyroxene).

(3) *Gabbro* and *basalt* differ from diorite in that the dark minerals (hornblende, pyroxene, and olivine) predominate. All feldspar is plagioclase; and biotite though present in some gabbros, is distinctly uncommon.

(4) *Obsidian* and *pitchstone* correspond in composition to granite and rhyolite. Both are commonly referred to as *volcanic glasses.* Obsidian is dark-colored to black and with a brilliant

luster (③ of fig. 8); pitchstone is lighter colored and with a dull luster.

(5) *Pumice* is a porous or cellular glass usually white or gray in color.

*g. Primary Structural Features of Igneous Rocks.* At the time igneous rocks are formed, they may acquire certain primary structural features that can be helpful in their field identification. With the exception of those varieties which exhibit a glassy texture, igneous rocks are composed of interlocking grains of different minerals. On this basis they can be distinguished from crystalline sedimentary and massive metamorphic rocks which normally contain crystals of the same mineral. Other distinctive structural features common to some but not all igneous rocks are as follows:

(1) Flow structure may be exhibited by the glassy-textured igneous rocks such as obsidian and by the fine-grained extrusives such as basalt.

(2) Tiny spherical, almond-shaped openings formed by gas bubbles in or rising through the lava, are commonly present in extrusive igneous rocks. These openings are called *vesicles.* A rock with such a structure is referred to as being *scoriaceous* (fig. 9).

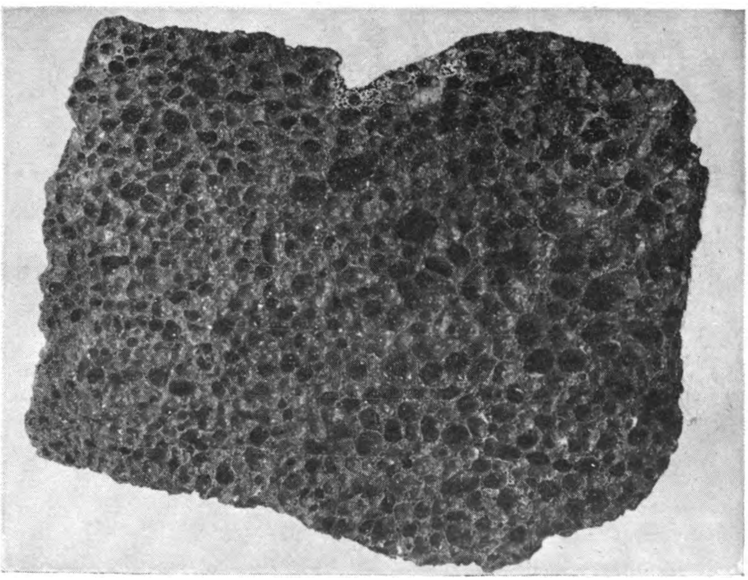


*Figure 9. Scoriaceous structure in extrusive lava rock.*

(3) Some of the coarser-grained igneous rocks may exhibit a more or less perfect *lamellar* or platy structure due to the parallel orientation of such minerals as mica and hornblende.

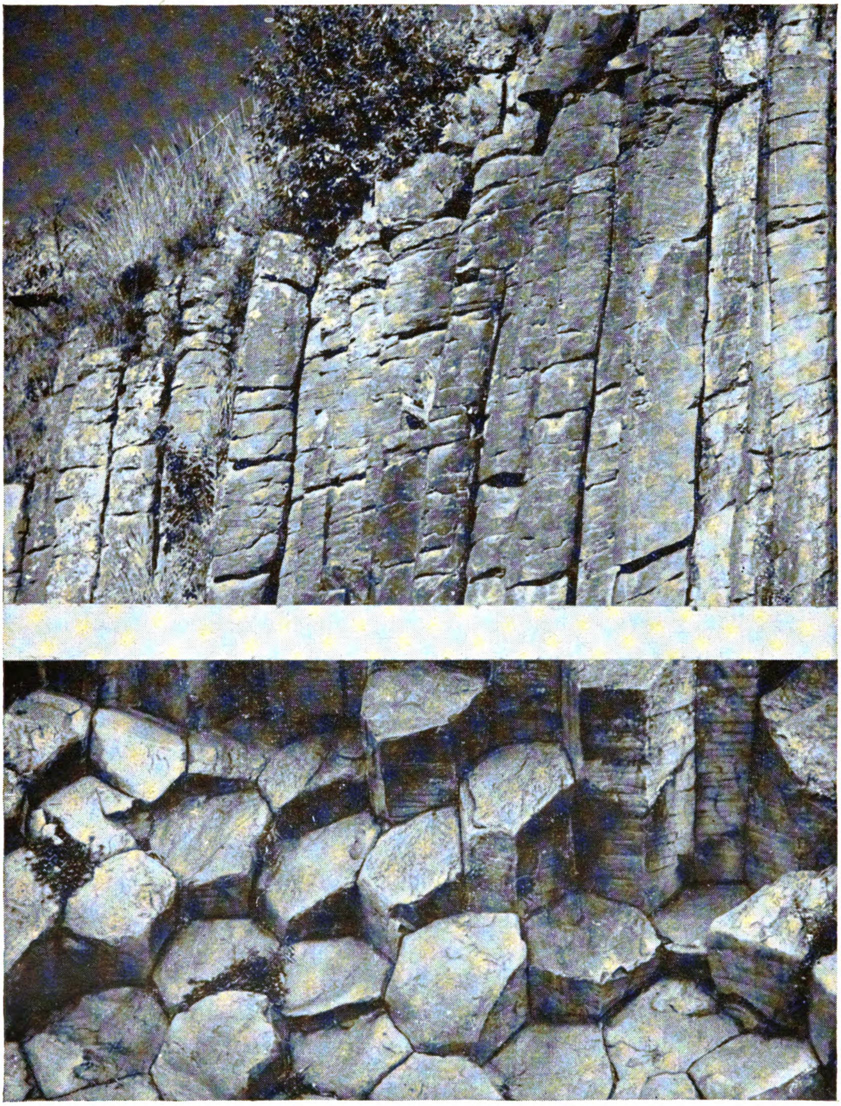


*Figure 10. Columnar jointing in basaltic sill. Hidalgo, Mexico. Upper photo is a side view of sill showing regular arrangement of columns; lower photo is sectional view showing irregular hexagonal outline of each column.*

This feature most commonly occurs near the contacts of intrusive bodies where the friction between the wall rock and the molten material causes the platy minerals to aline themselves in the direction of flow.

(4) Fine-grained igneous rocks often exhibit a *columnar* structure due to the development of shrinkage cracks (joints) which form as the molten mass cools and solidifies. This structural feature is commonly found in basaltic intrusions, such as dikes and sills, that cooled at a moderate rate of speed (fig. 10).

## 13. Sedimentary Rocks

*a. Definition.* *Sedimentary rocks,* known also as stratified rocks, are of secondary origin. They are formed of layer-like masses of sediments that have been made coherent through cementation, compaction, or recrystallization. *Sediment,* in turn, may be defined as material derived from any source whatsoever (preexistent rocks, organic material, volcanic ejecta, and the like) that has been transported by some medium from its place of origin to a place of final deposition. The most common agency of transportation is water, but many sediments are deposited on land by wind and ice.

*b. Mode of Origin of Inorganic Sediment.*

(1) The inorganic material entering into the composition of most sedimentary rocks is derived from the disintegration and decomposition (par. 19) of preexistent igneous, sedimentary, and metamorphic rocks. This material is then moved from its original position in the form of solid particles or dissolved salts. Rock particles dropped from suspension produce deposits of *clastic* or *fragmental* sediment. By chemical reaction, the dissolved salts become insoluble and form *precipitated* sediments; or, by evaporation of the water medium, they form *evaporites.*

(2) The relative magnitude of pyroclastic deposits is not too well known, but it appears that they constitute only a small part of the sedimentary rocks in the earth's crust. However, the quantity of material which can be ejected at a single volcanic eruption and transported by the wind is quite large. For example, Katmai, which erupted in Alaska in 1912, is estimated to have ejected 5 cubic miles of ash.

*c. Mode of Origin of Organic Sediment.* The organic material entering into the composition of a very small percent of the total sedimentary rock mass is the result, either directly or indirectly, of the activities of plants and animals. Included in this group are certain protective and supporting structures produced by plants and animals which on the death of the organism become sediments and certain precipitated sediments formed by the activities of organisms.

*d. Classification of Sediment.* Many different classifications of sediment have been proposed and many are in use. Based on the agent of deposition, sediments are classified as *fluviatile,* stream-borne deposits; *marine,* sea deposits; *aeolian,* wind-borne deposits; and *glacial,* ice or glacier deposits. This classification, although generalized, is quite useful. Based on the mode of origin, sediments can be classified as *clastic, chemical,* and *organic.* This classification is more practicable, since it covers both the physical properties and chemical constituents ((1) and (2) below).

(1) *Clastic sediments.* The clastic or *fragmental* sediments include gravel, sand, silt, and clay which are differentiated by the dimensions of the particles. Composition is indirectly inferred since the predominant mineral in sand is quartz, and the principal minerals in clay are kaolinite, montmorillonite, and illite. All kinds of rock contribute to clastic material. Each size of clastic particle may be transported by several agencies. The terms gravel, sand, silt, and clay as used in the Department of the Army Unified Soil Classification System (table IV) are defined as follows:

(*a*) *Gravel.* Gravel consists of rock grains or fragments with a diameter range of from 76 mm (3 in) to 4.76 mm (retention on a No. 4 sieve). The individual grains are usually more or less rounded. Gravel will vary in character in different regions according to the type of rock from which it is derived.

(*b*) *Sand.* Sand consists of grains with a diameter range of from 4.76 mm (passing No. 4 sieve) to 0.074 mm (retention on a No. 200 sieve). Sedimentary sands may vary greatly in size, shape, and mineral composition. Although comparatively rare, residual sand grains are usually angular and are not always likely to be composed of resistant minerals.

(*c*) *Silt.* Silt consists of grains with a diameter range of from 0.074 mm (passing a No. 200 sieve) to 0.005 mm. The individual grains are largely angular in shape. In the Army's Unified Soil Classification System, silt and clay are considered *fines* and are differentiated wholly on a physical basis, not by the dimensions of the particles. On a physical basis, silt has little plasticity, has little dry strength, and feels smooth in contrast to the grittiness of fine sand.

(*d*) *Clay.* Clay consists of flat particles which have diameters of less than 0.005 mm. It is sponge-like and elastic and has pore spaces filled with water. It is plastic through a wide range of water content. Organic clay is clay containing at least 3 percent carbonaceous material. Clays may be of two general types, residual and stratified. Residual clays are formed by the decay of rock in place and usually show a transition from clay at the surface to the parent rock below. Such clays may vary in type from sandy clays to those of high plasticity. Stratified clays occur in beds or lenses of variable thickness and character. They may be interbedded with other types of sediment.

(2) *Chemical and organic sediments.* The chemically deposited and organic sediments are classified on the basis of chemical composition. The common sediments, formed chemically by precipitation and evaporation and through the life processes of organisms, are listed in table II.

*e. Consolidation of Sediment to Form Sedimentary Rocks.* The conversion of sediment into rock, sometimes called *lithification,* is brought about by compaction, cementation, or recrystallization, and is rarely the work of any one single process. These processes are described as follows:

(1) *Compaction.* Ultimate consolidation of sediments can be accomplished as a result of long periods of pressure due largely to the weight of overlying materials. The pressure expels the water in the sediment and brings the rock or mineral particles closer together. This type of consolidation operates most effectively on fine-grained sediments like silts and clay (conversion of clay to shale) and on organic sediments (conversion of peat to coal).

(2) *Cementation.* In porous material through which water can circulate, minerals in solution may be precipitated. Cemen-

tation occurs when these minerals eventually fill the voids between particles and bind the fragments together. The most common cementing materials are silicon dioxide (quartz), calcium carbonate (calcite), and the iron oxides (limonite and hematite).

(3) *Recrystallization.* Chemical recombination of dissolved minerals in permeating water may bring about the continued growth of the mineral grains in a sediment or the development of new minerals. This growth or development gives some coherence to the mass and develops a rock with an interlocking, crystalline fabric or grain. Lime sediment, for example, is readily converted into crystalline limestone or even dolomite by this process.

*f. Classification of Sedimentary Rocks.* For the purpose of this manual, sedimentary rocks are classified as clastic, chemical, or organic, based upon the mode of origin of the sediment (par. 13*d*) from which they are derived. The clastic rocks commonly show separate grains. The chemical precipitates and evaporites, on the other hand, either have interlocking crystals or are in earthy masses. The organically formed rocks commonly contain easily recognized animal and plant remains, such as shells, bones, stems, or leaves. Table II lists the common sedimentary rocks and the sediment or material from which they have been derived.

*Table II. Common sedimentary rocks.*

| Type | Sediment | Rock |
|---|---|---|
| Clastic or fragmental | Coarse (gravel) | Conglomerate. |
| | Medium (sand) | Sandstone. |
| | Fines (silt and clay) | Siltstone and shale. |
| Pyroclastic | Coarse (cinder) | Agglomerate. |
| | Fine (ash) | Tuff. |
| Chemical precipitates and evaporites. | Calcium carbonate ($CaCO_3$) | Limestone. |
| | Calcium magnesium carbonate ($Ca(Mg,Fe)(CO_3)$). | Dolomite. |
| | Silicon dioxide ($SiO_2$) | Chert. |
| | Calcium sulphate ($CaSO_4 \cdot 2H_2O$) ($CaSO_4$). | Gypsum Anhydrite. |
| | Sodium chloride (NaCL) | Rock salt. |
| Organic | Calcium carbonate (animal remains). | Coquina, some coral rock, and chalk. |
| | Carbon (plant remains) | Coal. |

*g. Minerals in Common Sedimentary Rocks.* To analyze their mineral content sedimentary rocks are divided into three major types: sand, clay, and lime. The sand and clay types are principally clastics; the lime type includes the precipitates and the calcium carbonates of organic origin.

(1) *Sand type rocks.* The minerals which are commonly found in the predominantly sand type rocks, such as conglomerate (fig. 11) and sandstone, are:

Quartz, as grains
Feldspar, as grains
Mica minerals, as small plates
Clay minerals
Limonite, Hematite, Calcite, Quartz — as cementing material

*Figure 11. Conglomerate.*

(2) *Clay type rocks.* The minerals which are commonly found in the predominantly clay type rocks, such as shale and siltstone, are:

Clay minerals
Quartz, as fine grains

Mica minerals, as fine plates
Limonite
Hematite
Calcite
Quartz
} as cementing material

(3) *Lime type rocks.* The minerals commonly found in the predominantly lime type rocks, such as limestone, chalk, coral rock, dolomite, and coquina, are:

Calcite, as visible grains or crystals
Dolomite, as visible grains or crystals
Quartz, as grains
Chalcendony or chert, as grains
Clay minerals
Lime mud
Limonite
Hematite
Quartz
} as cementing material

*h. Primary Structural Features of Sedimentary Rocks.* The primary structural features inherent in the sediments before consolidation are valuable not only in the field recognition of sedimentary rocks but also in determining the conditions under which the sediment originated. Those structural features of principal importance are stratification, including lamination; bedding fissility; cross-bedding; mud cracks; ripple marks; and fossils.

(1) *Stratification.* A universally prevalent structural feature of

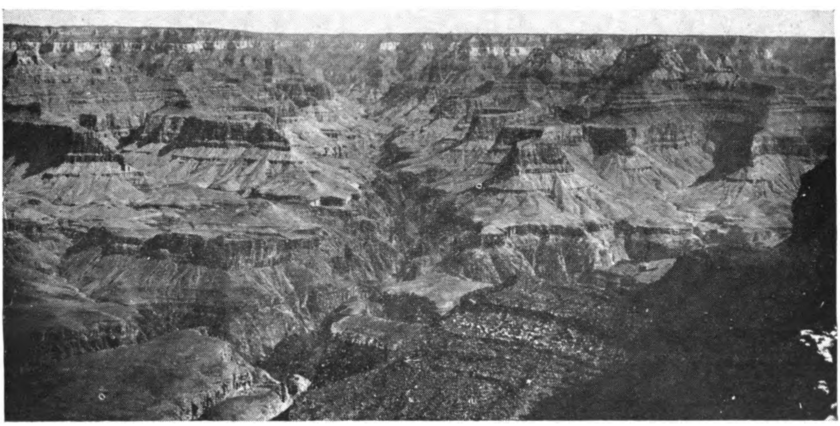


*Figure 12. Stratification in sedimentary rocks. Grand Canyon, Arizona-Utah.*

sedimentary rocks is their stratification as indicated by differences of composition, texture, hardness, or color disposed in approximately parallel bands (figs. 12 and 13). These strata may be flat-lying or nearly so, as originally deposited; or they may be tilted or folded, as a result of movement within the earth's crust (pars. 44–48). Each stratum is separated from the one immediately above and below by more or less definite planes known as *bedding planes* or *planes of stratification.* The thicknesses of sedimentary strata vary, but a large majority of the beds will range in thickness from a few inches (*thin-bedded*) to a few feet (*thick-bedded*). Very thin beds are referred to as *laminae.*

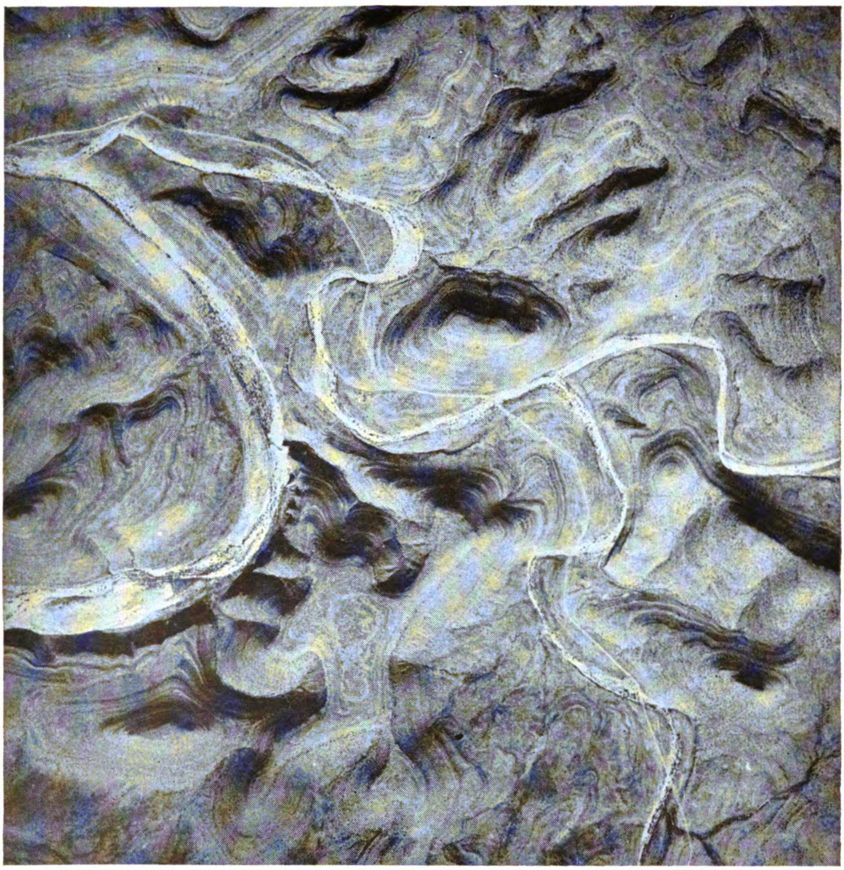


*Figure 13. Aerial view of flat-laying startified rocks. USA-Mexico.*

(2) *Bedding fissility.* A primary cleavage structure developed parallel to the stratification of some fine-grained sedimentary rocks is called *bedding fissility.* The ability of these rocks to split along parallel planes is attributed, mainly, to compositional and grain-size variation between layers. Shale is a sedimentary rock which has bedding fissility.

(3) *Cross bedding* (fig. 14). Some sedimentary deposits, usually those composed of granular material such as sand, commonly exhibit laminae lying at an angle to the true bedding plane. This feature of sedimentary rocks is known as *cross bedding* or *cross lamination.*

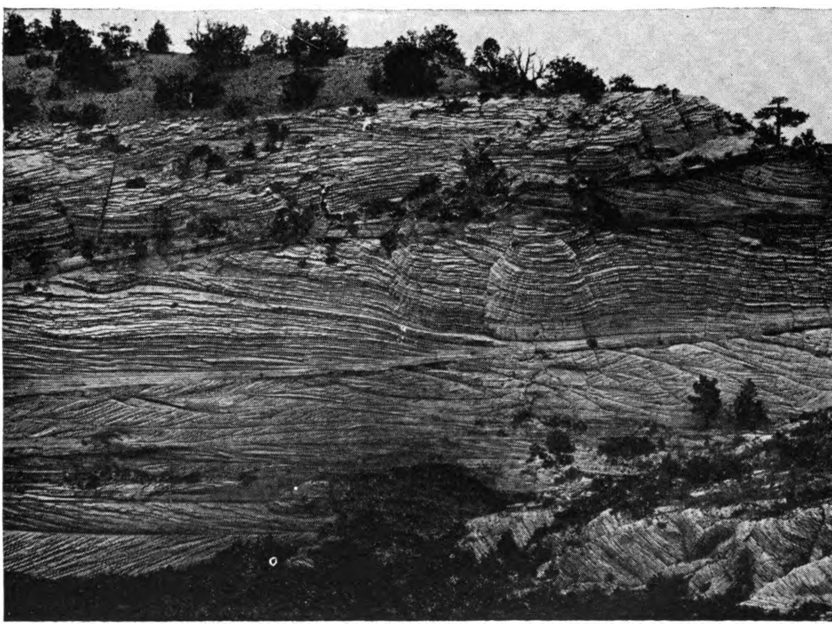


*Figure 14. Cross bedding. Central Utah.*

(4) *Mud cracks.* Sediment deposited in low, flat places, such as floodplains or rivers and intermittent lakes, usually develops *mud cracks.* The cracks, resulting from the loss of water contained in the sediment, separate the mass into irregular polygonal blocks which vary in size, shape, and arrangement according to the character of the sediment, rate of drying,

and many other factors. During exposure, the blocks become sufficiently hardened to be preserved during lithification of the sediment.

(5) *Ripple marks.* Parallel ridges, known as *ripple marks,* developed in sediment moved by wind or water are often preserved when the sediment is consolidated (fig. 15). Current- and wind-formed ripple marks (fig. 20) are asymmetrical in cross section. The current or windward side has a gentle slope, the leeward side has a steep slope. Movement of the transported material is in the direction of the leeward or steep slope.

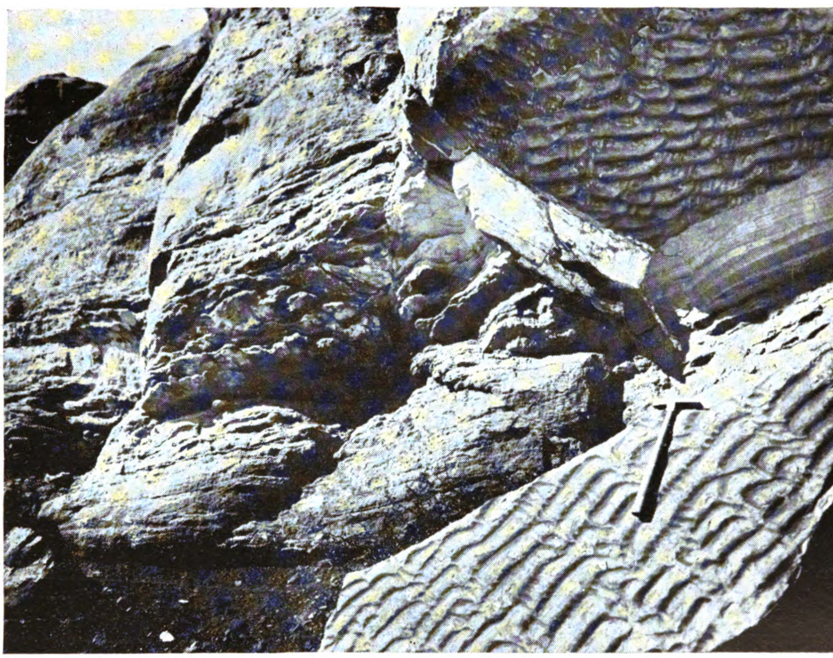


*Figure 15. Ripple marks preserved in sandstone. Fremont County, Wyoming.*

(6) *Fossils* (fig. 16). Although fossils, the remains or impressions of animals and plants, are not structural features, they are important in the field identification of sedimentary rocks. They are important because they were buried with the accumulating sediment.

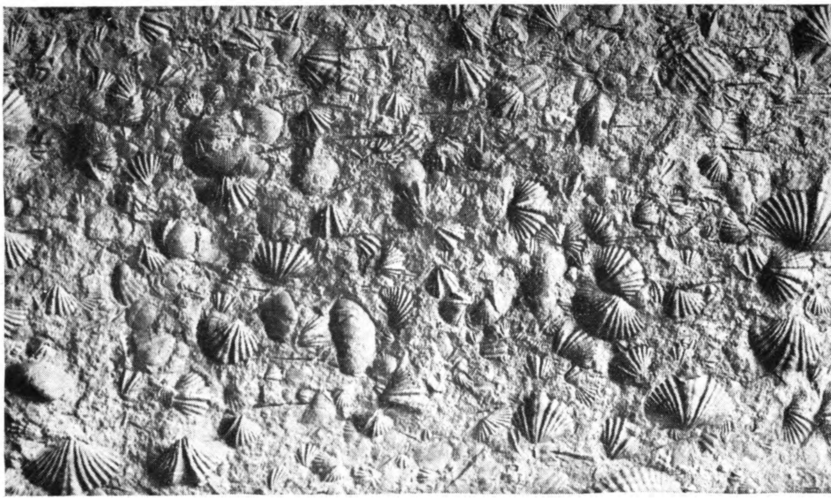


*Figure 16. Fossiliferous limestone.*

## 14. Metamorphic Rocks

*a. Definition. Metamorphic* rocks are those formed from preexistent igneous or sedimentary rocks as a result of an enforced adjustment of these rocks to environments different from those in which they were originally formed. This adjustment may include the formation within the rock of new structures, textures, or minerals, or all of these. It may have a lateral gradation ranging from inches to miles and from the original parent rock to its highly metamorphosed derivative.

*b. Mode of Origin.* Temperature, pressure, and chemically active fluids and gases are the major factors involved in metamorphism. The various factors are so interrelated that it is difficult to attribute the change inflicted on the rock to any one agency. For example, many chemical reactions which take place at high temperatures do not occur at low or normal temperatures. Also, heat increases the plasticity of minerals, thereby aiding the deformational forces of pressure in altering the original rock. The metamorphic work each factor is capable of accomplishing individually, is as follows:

(1) *Temperature.* The effect of heat is two-fold. It increases the solvent action of fluids and it helps break up and change chemical compounds. Extremely high tempratures may result from the intrusion of molten masses. The zone of altered rock formed adjacent to the molten mass is called the *contact*

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*metamorphic zone* (fig. 3). Heat may also be a normal complement to the depth to which the rocks are buried. In this case the earth's own heat produces metamorphism and the process is called *geothermal metamorphism.*

(2) *Pressure.* The compressive forces which accompany mountain building and other disturbances in the earth's crust (par. 48) are in the main responsible for the pressures to which many rocks are subjected. By the action of these movements, rocks could be produced in which the crystals, grains, and rock fragments are flattened and elongated or pulverized as a result of the force.

(3) *Fluids and gasses.* Water is the most important of the liquids and gasses involved in metamorphism. Under heat and pressure water becomes a powerful chemical agent. It acts as a solvent, promotes recrystallization, and takes part in the composition of minerals for which it is essential.

***Figure 17. Foliation in metamorphosed sedimentary rocks.***

Water may be reinforced locally by carbon dioxide and by fluids issuing from igneous magmas.

*c. Classification of the Common Metamorphic Rocks.* Metamorphic rocks, on the basis of their primary structure, are readily divided into two descriptive groups: the foliates and nonfoliates. The *foliated* metamorphic rocks display a pronounced primary structure, in that they have a banded appearance as a result of the differential pressures to which they have been subjected (fig. 17). The *nonfoliated* or *massive* metamorphic rocks exhibit no primary structural features. Metamorphism has apparently been limited to the process of recrystallization without the action of differential pressures. These structural differences are used as the basis for the simplified classification of the common metamorphic rocks listed in table III.

*Table III. Common metamorphic rocks.*

| FOLIATED | | |
|---|---|---|
| **Texture** | **Rock** | **Characteristics** |
| Coarse-grained | Gneiss | Streaked or banded; imperfectly foliated. |
| Medium-grained | Schist | Well-foliated; splits easily; generally rich in mica. |
| Fine-grained | Slate | Splits readily into smooth sheets. |
| **NONFOLIATED OR MASSIVE** | | |
| **Mineral content** | **Rock** | **Characteristics** |
| Chiefly quartz | Quartzite | Hard and brittle. |
| Chiefly calcite (or dolmite). | Marble | |
| Chiefly hydrous magnesium silicate. | Some types of serpentine. | Fairly soft; green. |

*d. Minerals and Structures in Common Metamorphic Rocks.*

(1) *Gneiss* is characterized by a rough, relatively coarse banding or foliation. The bands, often of unlike minerals, commonly appear as alternating light and dark lens-shaped masses in the body of the rock. The common minerals or mineral

groups present in gneisses are: quartz, and the feldspar, mica, amphibole, and pyroxene mineral groups. The specific name assigned is determined by the conspicuous mineral in the rock. For example, gneiss with the predominance of the mineral hornblende would be called *hornblende gneiss*.

(2) *Schist* is more homogenous in appearance and composition than is gneiss. The foliae are much thinner, generally more uniform in thickness, finer-textured, and often folded or "crinkled" to a much greater degree than the bands of most gneisses. The minerals are, in general, the same as for gneiss except that talc, chlorite, serpentine, and graphite may be dominant in some schists. As in gneiss, the specific name of a schist is determined by the predominant mineral present.

(3) *Slate* is very fine-grained and homogenous. Foliation is developed to a very great degree, enabling the slate to split into thin sheets with relatively smooth surfaces. The predominant minerals present in slate are those of the clay type sedimentary rocks (par. 13g (2)).

(4) *Quartzite* is a metamorphic rock derived from the recrystallization or cementation by quartz of sandstone or siltstone. Quartzite formed by recrystallization bears litle resemblance to the parent rock. That formed by cementation exhibits the same physical appearance as the rock from which it was derived. Differentiation between the quartzite resulting from cementation and the sedimentary rock from which it was derived, therefore lies in the degree of cementation. The degree of cementation is reflected in the appearance of a fresh fracture. In quartzite the cementing material is as hard as the sand or silt grains and, therefore, the fracture surfaces are smooth. In sandstone or siltstone the cementing material is weaker than the sand or silt particles and, therefore, the fracture surfaces are rough. The rough surface is produced by the sand or silt grains which stand above the fractured surface of the weaker cementing material.

(5) *Marble* is a massive metamorphic rock having essentially the same mineral content as the lime type sedimentary rocks (par. 13g (3)) from which it is derived.

*e. Primary Structural Features of Metamorphic Rocks.* There is no primary structural feature common to all varieties of metamorphic rocks. Most of them, however, exhibit foliation (fig. 17) which was

developed when the rock was subjected to differential pressures. This foliation is largely due to the orderly, parallel arrangement of platy or lamellar minerals, such as the micas. The degree of foliation depends on the constituents of the rock as well as on the intensity of the deformational forces.

## 15. Engineering Properties of Rocks

Excluding the effects of weathering (par. 19) which weakens and disintegrates the rocks near the earth's surface, the physical properties of a rock are affected by: the properties of the constituent minerals; the degree to which the mineral grains are bound together; the size and arrangment of the grains which produces such structures as banding and foliation; and the degree of fracturing, jointing (pars. 44–48) and bedding of the rock mass. These physical properties are the least variable in most igneous rocks, excluding the effects of fracturing (and weathering). Sedimentary rocks, on the other hands, are so variable that it is difficult to characterize their physical properties which may range between wide limits. Sandstone, for example, ranges from a rock so friable that it can be crushed with the fingers to a strongly cemented rock approaching quartzite in strength and hardness. Also, the sand, clay, and lime sediments exist in all conceivable mixtures. As a result, gradational sedimentary rock types are formed, for example, sandy shale, clayey sandstone, sandy limestone, and the like. Average or typical ranges in properties can be established for sound, unweathered specimens of the common rock types, but in practice each deposit must be evaluated individually. Some of the important rock properties of engineering significance are:

*a. Weight.* The heaviest rocks are the dark igneous and metamorphic rocks, such as basalt, gabbro, and some schists, which have an average specific gravity of 2.9 to 3.2. The other dense, compact rocks such as granite, slate, marble, and some limestones have a specific gravity of about 2.5 to 2.8. The lightest rocks are the sedimentary and volcanic rocks, such as chalk, tuff, and pumice, which contain many voids. Pumice is generally so light that it floats in water.

*b. Porosity.* In general, the strongest rocks are most dense and the weakest rocks are most porous. Porosity of granite and similar igneous rocks and of most metamorphic rocks is low, generally less than 1 percent. Basalt is similarly dense, but in certain areas it may contain many small cavities and in other areas be extremely porous. Porosity

of limestone ranges from 0.5 to 15 percent and in unusual types, such as coquina, up to 25 percent. The porosity of sandstone is typically high, ranging from 5 to 25 percent.

*c. Strength and Hardness.* Among the strongest and hardest rocks are quartzites, igneous rocks like granite and basalt, sound gneiss, and some schists. Compressive strengths of 15,000 to 30,000 pounds per square inch or more can be obtained. Some of the hardest, densest sandstones and siliceous limestones approach these strengths. Most limestones, marbles, dolomites, and sandstones, however, are intermediate in strength and hardness, with compressive strengths of about 2,500 to 15,000 or 20,000 pounds per square inch. The weakest and softest rocks include tuff, shale, chalk, soft sandstone, salt, and gypsum. The softest rocks are easily cut with hand tools. Most limestones and marbles can be sawed. Sandstones, igneous rocks, and the metamorphic rocks composed of quartz and other hard minerals cannot be readily sawed or cut.

*d. Durability and Toughness.* The most durable rocks are igneous rocks and massive quartzite and gneiss, but they do not resist fire, which causes cracking and spalling. Of these rocks the fine-grained varieties, such as basalt, are generally tougher and wear better under abrasion than coarse-grained varieties. Foliated and laminated metamorphic rocks, such as schist and slate, are hard but split readily and fall apart under abrasion. In general, limestones and sandstones are moderately tough under abrasion. Limestone, and sandstone with limy cement, are corroded by water or atmosphere containing acids. Chalk and some tuff are highly desirable for light construction because they are soft and easy to handle but harden on exposure. Shale is weak, softens when wet, and disintegrates rapidly when exposed to weather.

## 16. Soil

*a. Definition and Mode of Origin.* As used in a broad sense by engineers and in this manual, *soil* refers to the entire thickness of unsolidated material that overlies bedrock and is clearly distinguishable from the bedrock. Soil is composed principally of the disintegrated and decomposed products of rock. It includes air and may include water as well as organic matter derived from the decomposition of plants and animals. The weathering processes which contribute to the formation of soil are discussed in paragraphs 18–22.

*b. Soil Classification.* Several systems of soil classification are used.

The *geological classification* is based on the mode of origin of the soil (*c*) below. The *pedological classification* is based on soil-profile characteristics as they are related to soil-forming processes (par. 18). The *Army classification,* first adopted in 1942, is based on particle size and engineering properties of the soil (table IV).

*c. Types of Soil Deposits.* The soil types based on mode of origin are sedentary and transported.

(1) *Sedentary soils.* Sedentary soils include all deposits derived by the process of rock weathering or from accumulation in place. They include *residual deposits* (fig. 18) and *cumulose deposits.* Residual deposits are derived from the decay of the immediately underlying rock. They exhibit a wide range of properties because of the diverse mineralogical nature of the parent rock and the great difference in climatic conditions under which they are formed. Cumulose deposits are formed in place from the accumulation of organic matter (together with small amounts of rock waste), such as peat deposits

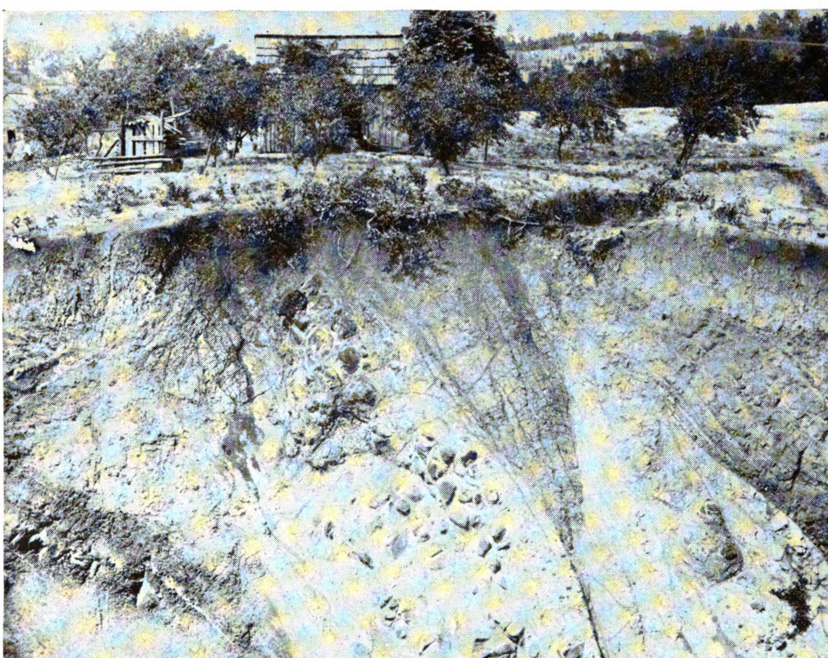

*Figure 18. Residual soil forming from the in-place weathering of igneous rock. Wadesborough, North Carolina.*

*Table IV. Department of the Army unified soils classification system (May 1951).*

| Major divisions | Letter symbol | Name | Field identification: Dry strength | Field identification: Other pertinent features | Laboratory classification tests |
|---|---|---|---|---|---|
| Coarse-grained soils: | | | | | |
| Gravels and gravelly soils. | GW | Gravel or sandy gravel, well graded. | None | Gradation, grain shape. | Sieve analysis. |
| | GP | Gravel or sandy gravel, poorly graded. | None | Gradation, grain shape. | Sieve analysis. |
| | GM | Silty gravel or silty sandy gravel. | None to slight | Gradation, grain shape, examination of fines. | Sieve analysis LL and PL on "Minus 40." |
| | GC | Clayey gravel or clayey sandy gravel. | Medium to high | Gradation, grain shape, examination of fines. | Sieve analysis LL and PL on "Minus 40." |
| Sands and sandy soils | SW | Sand or gravelly sand, well-graded. | None | Gradation, grain shape. | Sieve analysis. |
| | SP | Sand or gravelly sand, poorly graded. | None | Gradation, grain shape. | Sieve analysis. |
| | SM | Silty sand or silty gravelly sand. | None to slight | Gradation, grain shape, examination of fines. | Sieve analysis LL and PL on "Minus 40." |
| | SC | Clayey sand or clayey gravelly sand. | Medium to high | Gradation, grain shape, examination of fines. | Sieve analysis LL and PL on "Minus 40." |

| | | | | | |
|---|---|---|---|---|---|
| Fine-grained soils: | | | | | |
| Silt and clay soils (low liquid limit). | ML | Silts, sandy silts, gravelly silts or diatomaceous soils. | None to slight | Examination wet (shaking test). | Sieve analysis LL and PL on "Minus 40." |
| | CL | Lean clays, sandy clays, or gravelly clays. | Low to medium | Examination in plastic range. | Sieve analysis, if applicable LL and PL on "Minus 40." |
| | OL | Organic silts or lean organic clays. | None to slight | Examination in plastic range, color, odor, organic content. | LL and PL before and after oven drying. |
| | MH | Micaceous silts, diatomaceous soils or elastic silts. | None to slight | Examination wet (shaking test). | Sieve analysis LL and PL on "Minus 40." |
| | CH | Fat clays | High | Examination in plastic range. | Sieve analysis if applicable. LL and PL on "Minus 40." |
| Silt and clay soils (high liquid limit). | OH | Fat organic clays | Medium to high | Examination in plastic range, color, odor, organic content. | LL and PL before and after oven drying. |
| Fibrous organic soils. | Pt | Peat, humus, and other organic swamp soils. | Readily identified | | Consistency, texture, and water content. |

in ponds and lakes and ooze deposits in oceans. They may exhibit a wide range of properties because of the diverse nature of the protective and supporting structures of the organisms.

(2) *Transported soils* (figs. 19 through 23). Transported soils are soils that have been moved from the place of their origin and redeposited. The agencies of transportation are water, wind, ice, and gravity. Water-borne soils, the most important and widespread of the transported soils, are subdivided into alluvial, marine, and lacustrine soils, depending on the type of water body from which the deposits were laid down.

(*a*) *Alluvial soils* are almost wholly fragmental, consisting of mixtures of gravel, sand, silt, and clay. These soils occur in river valleys (fig. 19), deltas, and alluvial fans (par. 27*c*). They are formed when a stream loses its carrying power because of a reduction in its velocity. During this reduction in velocity the coarse materials are deposited first, and are followed by successively finer materials. Soils of this kind are therefore stratified or layered, but each layer is homogenous in texture. Mineralogically, al-

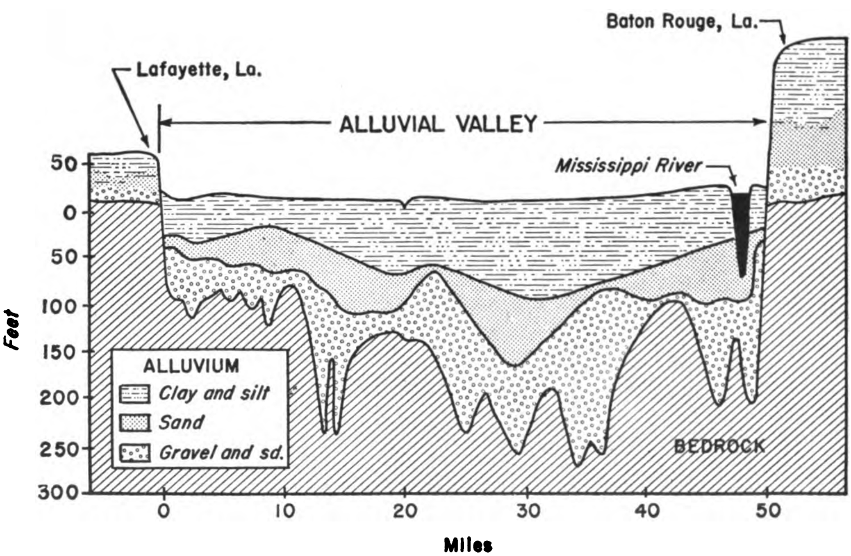


*Figure 19. Recent alluvium in alluvial valley of Mississippi River.*

luvial soils are related to the materials comprising the watershed of the stream by which they were transported.

(*b*) *Marine soils* are formed from materials carried into the seas by streams and by material eroded from the beaches by wave and tide action. Part of the material is carried out and deposited in deep water, and part is heaped up as beaches along the coast. The continual back-and-forth motion of sand on a beach is a very effective sorting mechanism, so that beach deposits commonly consist of sand or gravel of fairly uniform grain size. Bedding is often irregular as a result of alternating periods of high and low water. The bottom currents, which carry the clastic debris to the deeper water, sort the material effectively and spread it rather evenly over the submerged plains bordering the land. As a result, sea-floor deposits consist of extensive beds of uniform material, commonly dense, impermeable, plastic clay.

(*c*) *Lacustrine soils* are soils deposited in fresh-water lakes. They are fine-textured and plastic and are commonly salty, except at the surface in humid regions. They may be more permeable and may undergo fewer changes in physical properties when worked than do the marine soils.

(*d*) *Aeolian soils* are wind-transported soils (par. 30). The sand-size particles which are moved on or near the earth's surface accumulate into drifts called dunes (fig. 20); the silt-size particles carried in suspension for greater distances, form extensive deposits of material called *loess* (fig. 21). Dune sand typically has grains of uniform size, with

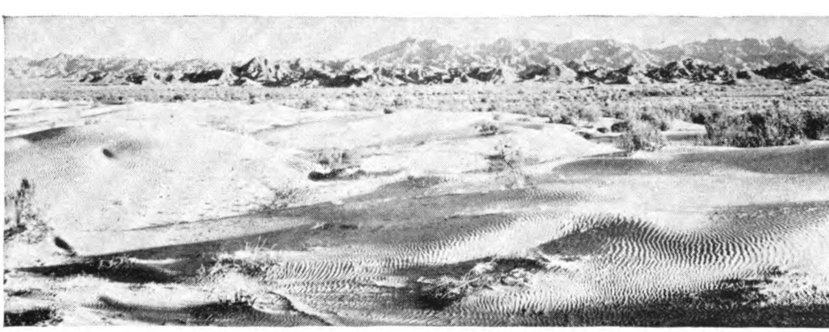

*Figure 20. Soil transported by wind and deposited in the form of dunes. Note ripple marks on surface of dunes. Southern California.*

practically no gravel and little silt or clay. The surface of the grains are usually chipped and pitted or "frosted," because of the innumerable sharp contacts with other grains or rock fragments. Loess is composed mainly of exceedingly fine, angular quartz grains and clay particles. It is commonly a soft, porous, yellow-brown material with a remarkable ability for standing in vertical walls.

*Figure 21. Loess deposits showing typical vertical face. Iowa.*

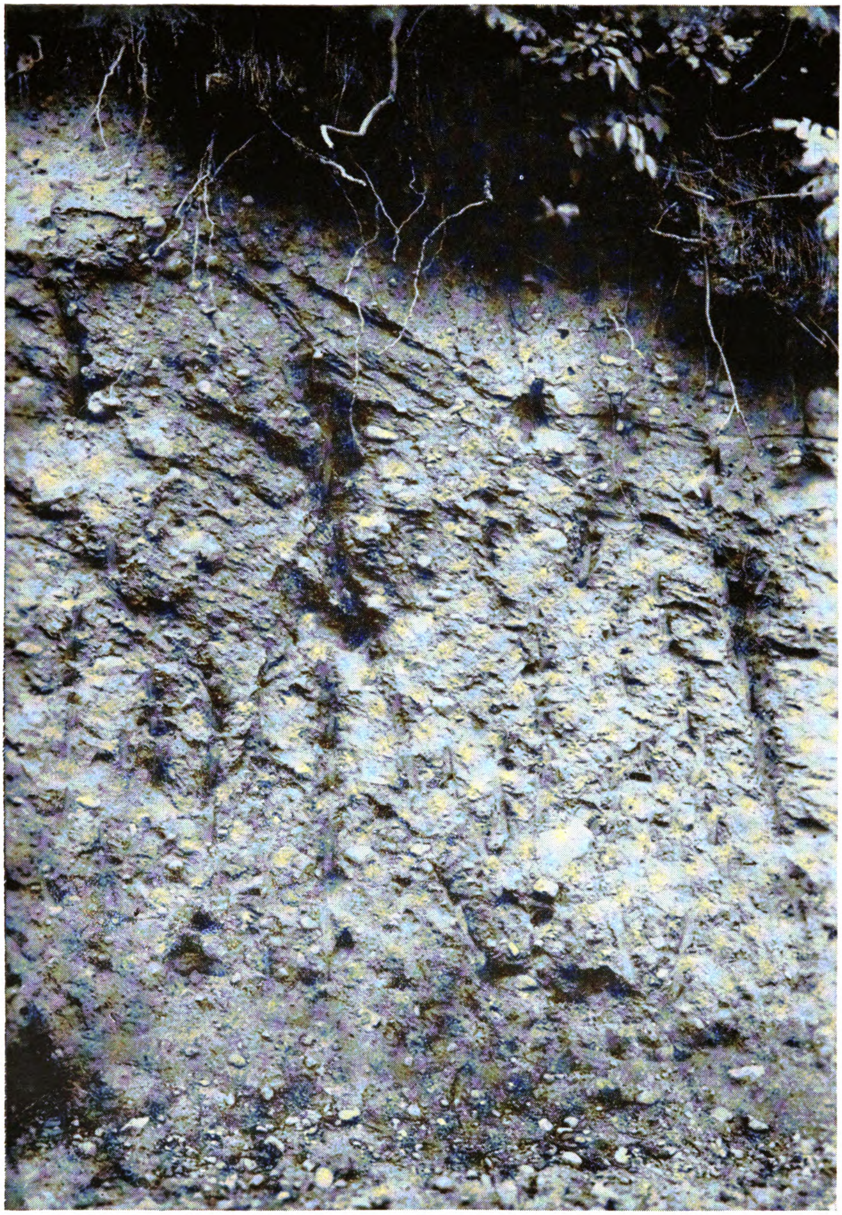

*Figure 22. Glacial till.*

*Table V. Engineering characteristics of soil pertinent to selection of foundation sites. (May 1951).*

| Letter symbol[1] | Name | Value as foundation when not subject to frost action[2] | Value as base directly under wearing surface[3] | Potential frost action | Compressibility and expansion | Drainage characteristics |
|---|---|---|---|---|---|---|
| GW | Gravel or sandy gravel, well-graded. | Excellent | Good | None to very slight. | Almost none | Excellent. |
| GP | Gravel or sandy gravel, poorly graded. | Good to excellent | Poor to fair | None to very slight. | Almost none | Excellent. |
| GM | Silty gravel or silty sandy gravel. | Good to excellent | Fair to good | Slight to medium. | Very slight | Fair to poor. |
| GC | Clayey gravel or clayey sandy gravel. | Good | Poor | Slight to medium. | Slight | Poor to practically impervious. |
| SW | Sand or gravelly sand, well-graded. | Good | Poor | None to very slight. | Almost none | Excellent. |
| SP | Sand or gravelly sand, poorly graded. | Fair to good | Poor to not suitable. | None to very slight. | Almost none | Excellent. |
| SM | Silty sand or silty gravelly sand. | Good | Poor | Slight to high. | Very slight | Fair to poor. |
| SC | Clayey sand or clayey gravelly sand. | Fair to good | Not suitable | Slight to high. | Slight to medium. | Poor to practically impervious. |
| ML | Silts, sandy silts, gravelly silts, or diatomaceous soils. | Fair to poor | Not suitable | Medium to very high. | Slight to medium. | Fair to poor. |
| CL | Lean clays, sandy clays, or gravelly clays. | Fair to poor | Not suitable | Medium to high. | Medium | Practically impervious. |
| OL | Organic silts or lean organic clays. | Poor | Not suitable | Medium to high. | Medium to high. | Poor. |

| | | | | | | |
|---|---|---|---|---|---|---|
| MH | Micaceous clays or diatomaceous soils. | Poor | Not suitable | Medium to very high. | High | Fair to poor. |
| CH | Fat clays | Poor to very poor. | Not suitable | Medium | High | Practically impervious. |
| OH | Fat organic clays | Poor to very poor. | Not suitable | Medium | High | Practically impervious. |
| Pt | Peat, humus, and other organic swamp soils. | Not suitable | Not suitable | Slight | Very high | Fair to poor. |

[1] For explanation of letter symbol, see table IV.

[2] Values are for subgrades and base courses except for base course directly under wearing surface.

[3] The term "excellent" has been reserved for base materials consisting of high quality processed crushed stone.

*Figure 23. Stratified glacial drift consisting of interbedded sands and gravels.*

(*e*) *Glacial soils,* called *drift,* are soils that have been carried within or upon an advancing ice sheet or that have been pushed ahead of it. During the retreat of the ice sheet, these soils were deposited in a variety of physiographic forms, such as moraines, kame terraces, eskers, and outwash plains (par. 29*d*). In some of these physiographic forms, such as moraines, the soil is composed of mixed and unstratified boulders, gravels, sands, and clays. This material, resembling unconsolidated conglomerate, is called *till* (fig. 22). When decomposed by weathering, till is called *gumbotil.* In the other physiographic forms, such as kame terraces, eskers, and outwash plains, the soils consist of stratified and partly sorted stream gravels, sands, and fines transported outward from the glacier by streams arising from the melting ice (fig. 23).

(*f*) *Colluvial soils* are mixed deposits of rock fragments and soil material accumulated at the base of comparatively steep slopes through the influence of gravity. They include creep and local wash (par. 24).

## 17. Engineering Properties of Soil

The complexities of soil as engineering material are the concern of a branch of engineering termed *soil mechanics*, which is covered in other publications (app. I). The engineering properties of soils, pertinent to selection of foundation sites are given in table V, which is a continuation of table IV.

# Section II. WEATHERING AND ITS PART IN SOIL FORMATION

## 18. General

*a.* The hardest rock, when exposed to the weather long enough, is ultimately broken down into loose unconsolidated material the geologist calls *mantle* and the engineer calls *soil* (par. 16). Microorganisms and higher forms of life invade the surface and interior of the mantle and, in time, the original material becomes much altered in its appearance and inherent properties. New material is formed, and new physical and chemical properties are acquired. This modified uppermost portion of the mantle, because it supports plants, is the main concern of agriculturists and pedologists. To them, only this upper portion is "soil." Because most engineering activity takes place on or within the uppermost portion of the mantle, the engineer must know the special characteristics of this upper portion and the processes that produce them.

*b.* This section discusses the weathering processes responsible for producing the engineer's soil (par. 20) and the "soil-forming processes," in the restricted sense, responsible for producing the pedologist's soil and soil layers (par. 21*a*(2)). The engineering properties and classification of soils are discussed in paragraphs 16 and 17 of the previous section.

## 19. Weathering and Erosion

*a. Weathering. Weathering* is a general term which covers all static physical changes which tend to destroy the coherency of rock masses. The action of the physical agents alone, which results in the mechanical breakup of the rock into smaller particles without loss of identity, is called *disintegration.* The action of chemical agents, which destroys

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the identity of the minerals and forms new compounds, is known as *decomposition.* Disintegration (par. 20*a*) and decomposition (par. 20*b*) are so interrelated that a weathered surface cannot be attributed wholly to any single process, except in some areas where one effect predominates over the other.

*b. Erosion.* *Erosion* is a general term for all processes by which weathered products are removed and transported toward a place of final deposition either on land or in salt- or fresh-water bodies. The agents of erosion are streams, waves, glaciers, wind, and subsurface water (pars. 26–31), and gravity (pars. 23–25).

## 20. Weathering Processes

The transformation of rocks into mantle usually involves a considerable number of processes, which may act simultaneously or in sequence. The most important of these weathering processes are described below.

***Figure 24.** Mechanical weathering of granite by frost action forming slopes of talus. Hinsdale County, Colorado.*

*a. Mechanical Weathering (disintegration).* Mechanical weathering predominates in regions where the climate restricts chemical activity. When chemical decomposition is active, its intensity is greatly increased by the previous or concurrent disintegration of the rock. The following agencies contribute to mechanical weathering.

(1) *Frost action.* In regions where the winter temperature may fall below the freezing point of water, rocks are ruptured and wedged apart by the pressure exerted when the water is converted into ice. This is the only effective agent of weathering in polar regions. This quarrying power of frost is evidenced by the accumulation of angular rock debris, called *talus,* which collects at the base of cliffs or on steep mountain slopes (fig. 24). Mineral grains within the larger blocks of rocks can be wedged apart by this weathering process.

(2) *Temperature changes.* The mechanical breakdown of rocks in desert regions has been attributed by some to the stresses set up between the minerals in a rock mass when alternately heated by the sun during the day and cooled at night. Unequal expansion and contraction of the minerals are thought to result in the crumbling of the rock's surface or, in some cases, to expand the outer shell of the rock, causing it to peel off (exfoliate) (fig. 25). Disintegration by repeated heating and cooling of rock samples has not been satisfactorily proved by laboratory tests. *Exfoliation* is now generally attributed to chemical processes.

(3) *Plants.* Trees and shrubs have some importance in the mechanical disintegration of rocks. Rootlets invade small crevices and, by sheer force exerted during growth, slowly enlarge these openings even in the hardest rock (fig. 26). The amount of weathering accomplished by plants, however, soon becomes obscured by the increasing amount of chemical weathering along the enlarged openings in the rock mass.

(4) *Miscellaneous mechanisms.* Other agencies of limited importance in mechanical rock disintegration include the action of animals; crystal growth; crustal movements; and the impact of falling rocks, slides, and avalanches.

*b. Chemical Weathering (Decomposition).* Decomposition usually accompanies disintegration of rock masses. The increased number of

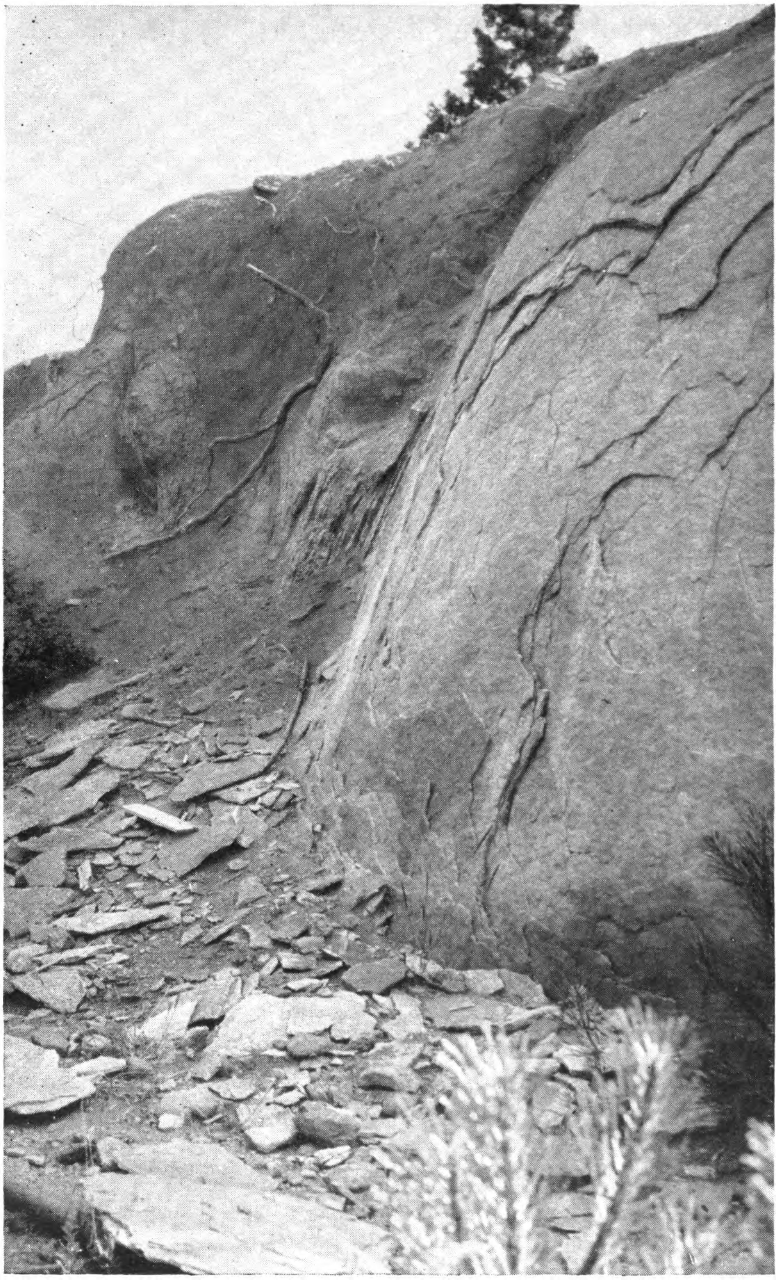

*Figure 25. Exfoliation. Near Nevada City, California.*

surfaces produced by mechanical weathering makes decomposition more effective. The rate of chemical weathering is strongly dependent upon climate and is governed by the mineralogical nature and texture of the rock under attack, the amount and composition of the water moving through the weathered zone, and the nature and rate of removal of the products formed. Several chemical reactions are usually simultaneously involved and are commonly interdependent. Processes contributing to the chemical weathering of rocks are discussed herewith.

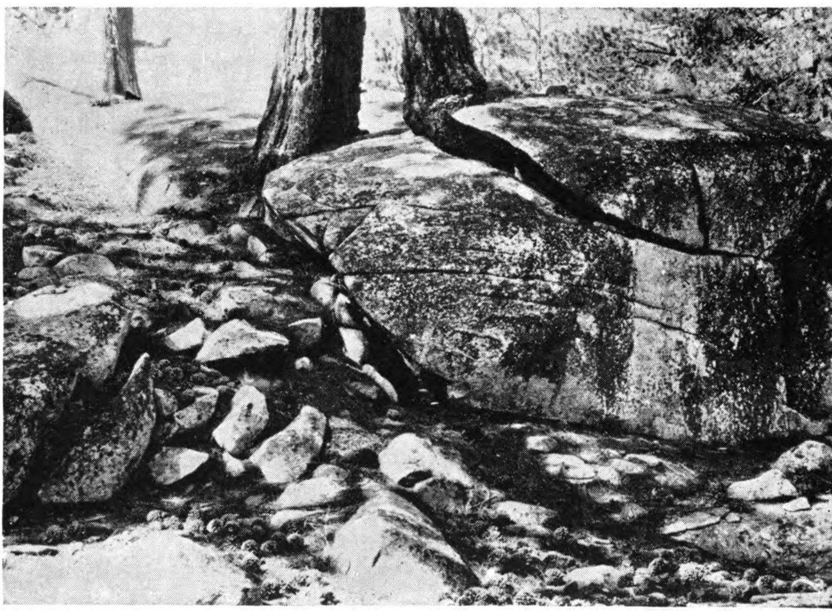

*Figure 26. Disintegration of rock masses produced by growth of roots in crevices in rocks.*

(1) *Hydrolysis.* Hydrolysis is the process by which water reacts with the minerals in rocks, forming secondary products. It consists of the interaction of minerals and water which results in an exchange of their component parts. For example, when water comes in contact with sodium carbonate the water and the carbonate react to produce sodium hydroxide and carbonic acid ($Na_2CO_3 + H_2O = 2\ NaOH + H_2CO_3$).

(2) *Hydration.* Water may also combine with minerals by merely converting them to a hydrate. Examples of this include the

conversion of hematite ($Fe_2O_3$) to limonite ($Fe_2O_3.H_2O$) and of the anhydrite ($CaSO_4$) to gypsum ($CaSO_4.2H_2O$). These transformations are commonly accompanied by an increase in volume and a reduction in hardness. This hydration makes the mineral more susceptible to other chemical reactions and hasten its decomposition.

(3) *Carbonation.* Carbon dioxide dissolved in water is a powerful tool in weathering. While it reacts with many minerals, its effect on carbonates is especially important. Bicarbonates with more solubility are formed, resulting in an increase in leaching losses and contributing to the disintegration of the rock. This reaction is the principal one involved in the chemical weathering of limestone.

(4) *Oxidation and reduction.* Changes in the state of oxidation of some of the elements, particularly iron and manganese, take place under certain conditions of the soil. A mineral powder containing iron or manganese when exposed to moderately dry air undergoes little or no change. When the powder is enveloped by water, however, hydrolysis converts some of the ferrous iron and the manganous form of manganese into a solution of slightly soluble hydroxides. These compounds can take up oxygen from the air to form more highly oxidized compounds with extremely low solubilities. Under certain soil conditions a reverse action may take place as in the case of loss of water by soil desiccation. Certain organisms associated with the decomposition of organic matter can extract oxygen from such compounds as ferric hydroxide when air is excluded by water. This change produces an iron compound of greater solubility. When soils are waterlogged for a considerable period, significant properties of the iron may be reduced, forming mottles of blue and gray. These oxidation and reduction changes may be important in soil-profile development.

(5) *Solution.* Water plays an important part in chemical weathering by serving as a medium for the reagents entering into chemical combination with minerals, and by removing certain minerals in solution. Among the materials most readily removed by solution are the compounds of potassium, sodium, calcium, and magnesium, found in the more soluble rocks such as gypsum, limestone, dolomite, and rocks containing

calcareous cement. Limestone can be used as a typical example of the chemical reactions leading to the destruction of these more soluble rocks. When carbon dioxide unites with water, carbonic acid is formed. This reacts with the calcite in the limestone to produce calcium bicarbonate which is soluble in water and is removed by percolating groundwater (fig. 27). Soils can be formed from limestones only when such impurities as are present have collected after the calcium carbonate is removed from the rock by percolation.

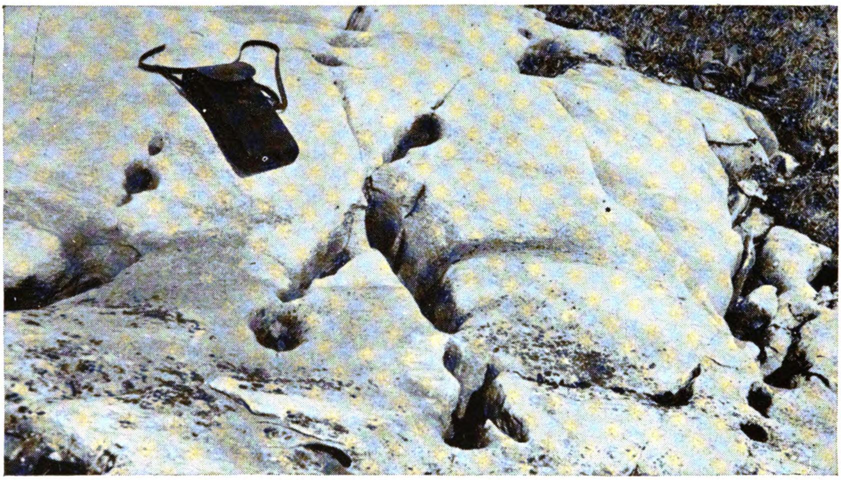

*Figure 27. Chemical weathering in limestone showing solution channels developing along joints.*

## 21. Soil Layers

*a. Soil Forming Processes and the Soil Profile.*

(1) The weathering processes (par. 20) produce the loose debris that mantles bedrock and accumlates at the base of outcrops on steep slopes. When the mantle remains essentially where it is formed, excluding movement due to gravity, it will reflect the charactistics of the rock from which it was derived (pars. 12–14), and it will grade imperceptibly into fresh, unaltered bedrock. When the mantle is moved from its point of origin by some transporting agency (pars. 26–31), it may

reflect the nature of the transporting agency, but it usually bears no resemblance to the underlying bedrock.

(2) In time, plants such as bacteria, mosses, and lichens that populate the mantle (residual or transported), and finally ferns, grasses, shrubs, and trees that gain a foothold, all gradually contribute organic matter. At the same time, air and water are admitted through the burrowing of rodents, earthworms, and ants, and the organic and inorganic matter in the mantle are mixed by these animals. The acids formed

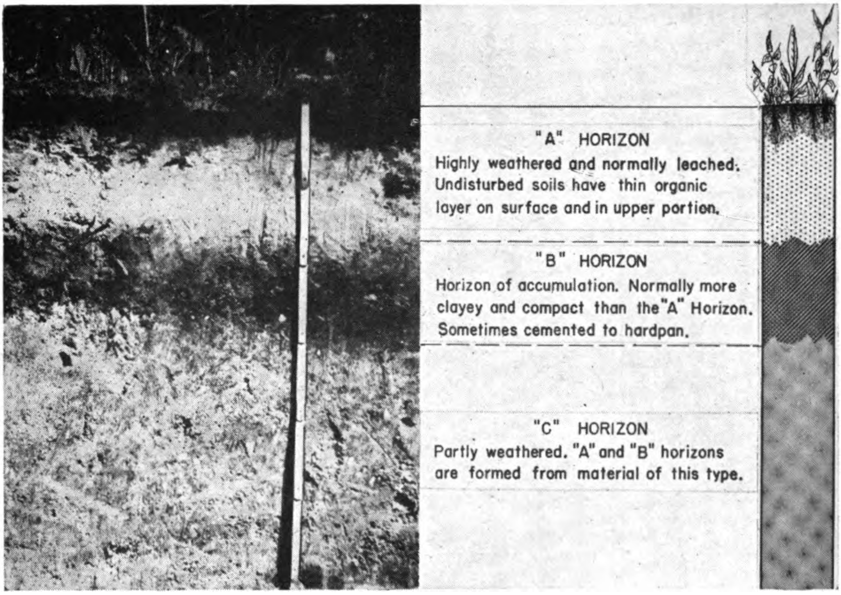


*Figure 28. Soil profile showing characteristic soil horizons.*

by the decaying organic material hasten the breakdown of inorganic matter. This breakdown of inorganic matter and the more intense weathering at the earth's surface modify the original properties of the mantle and produce a distinctive layering. This layering, called a *soils profile* (fig. 28), is distinctive of the climate and topographic environment. The more or less well-defined layers of a profile, with distinctive color, texture, structure, and consistency, are called *soil horizons*. The horizons are designated A, B, C, and D in

downward sequence. In general, the A horizon is characterized by leaching and the removal of material, the B horizon by accumulation and deposition of material. The C horizon is the transition zone containing partly weathered (disintegrated and decomposed) and unweathered fragments of the parent material. The D horizon is the unweathered material (bedrock or sedimentary soil). These zones are shown in figure 28.

*b. Factors in Soil Formation.* All soil-forming processes (pars. 20 and *a*(2) above) tend to obliterate the differentiating influence of parent material. They produce a soil, in the pedological sense, that is more dependent upon the climate, the relief of the land, and the length of time the soil-forming processes have operated. For instance, in any climate, young soils derived from different parent rocks may differ widely from each other. As these young soils grow older, weathering and organic processes may gradually lessen the differences between them; some constituents will steadily be removed, others will be concentrated.

(1) *Effects of climate.*

(*a*) Climate is accountable for striking differences in the rate and type of weathering, for the agency responsible for the removal and redeposition of the weathered material, and largely for the percolation of the water through the mantle.

(*b*) In regions of high humidity, the soils are more highly leached than those of semiarid and desert regions. Hydrolysis, carbonation, and other forms of chemical weathering are extremely rapid especially if the region is warm.

(*c*) In cold regions, freezing prevents the percolation of water and therefore, slows down the soil-forming processes. The structure and arrangement of soil particles are greatly modified by freezing and thawing.

(*d*) In arctic regions, where substrata are frozen throughout the year and where upper horizons freeze and thaw as the seasons change, the soil horizons become mechanically mixed and the soils remain in a poorly drained condition most of the time.

(2) *Effects of relief.* Relief is a factor in soil formation because of its influence on drainage, runoff, and other water effects, including erosion.

(3) *Effects of time.*

(*a*) Time is a very important factor in the formation of soils. For example, two calcareous drift deposits in eastern India have different depths to which the soil-forming processes have been able to penetrate. One deposit is leached free of lime to a depth of about 30 inches, the other to a depth of about 50 inches. The difference in depth of the leached zone represents the difference in time between the deposition of the two glacial drifts, which would probably be measured in thousands of years.

(*b*) Soils of high and steep mountains are normally young in years and stage of development because of rapid erosion. Flood-plain soils are also young because of the almost continuous accumulation of sediments.

*c. General Effects of Weathering.* Weathering generally increases the clay content of soils near the surface, making them more plastic and cohesive than the fresher, deeper soils. Extreme weathering, however, may cause a loss of some of these properties because of further changes in the mineralogical content of the clay fraction. Downward-percolating water removes colloidal clay particles and leaches soluble constituents from the surface soils, leaving a higher concentration of the relatively insoluble minerals. Both the clay particles and soluble salts may accumulate in the B horizon. Oxidation is more active in the surface layer which may be more colored by iron oxides than are the deeper horizons. Leaching tends to reverse this process.

## 22. Naturally Occurring Solidified Soil Layers

Several types of naturally solidified soil exist. The degree of solidification, the thickness, the stability, and the depth of occurrence vary widely. The most common types are *hardpan* and *laterite.*

*a. Hardpan.* A hardpan is an indurated (hardened) or cemented soil horizon, formed by the accumulation of clay, iron oxides, silica, or soluble salts such as calcium carbonate (fig. 29). The mode of formation and the materials involved are usually different in humid and arid regions.

(1) *Hardpans in humid regions.*

(*a*) During the weathering of soils in regions of high rainfall, large quantities of organic and inorganic materials may be carried downward from the soil surface. Since the

solubility of most of these materials is related to the acidity of the soil water, the materials are commonly deposited at points in the soil where the acidity or basicity undergoes a significant change. An example of this phenomenon is the deposition of organic colloids and sesquioxides in the B horizon. This zone of cementation may attain a thickness of several inches and may develop considerable strength.

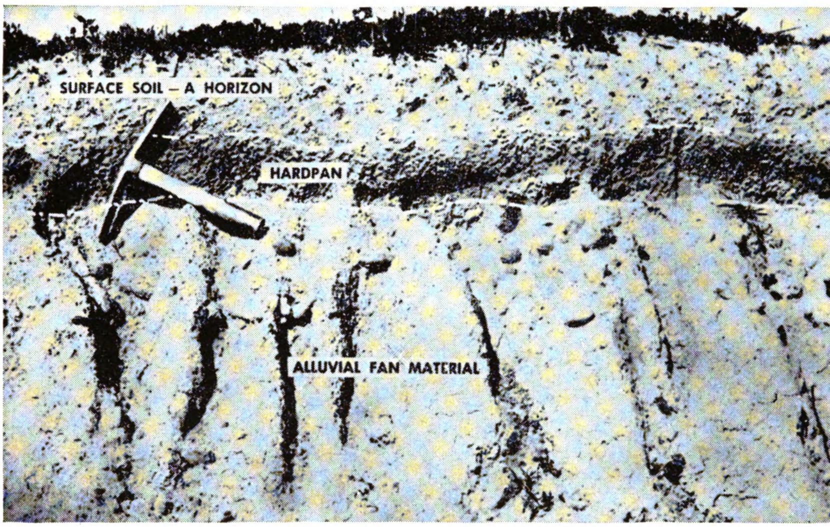


*Figure 29. Hardpan layer resulting from accumulation of iron oxide in the B horizon.*

(*b*) In a humid or subhumid climate, *clay pan* is developed on nearly flat upland surfaces. It is a dense and heavy B horizon that is hard when dry and plastic or stiff when wet. It is formed by the accumulation of clay brought in by percolating waters from the horizon above.

(2) *Hardpans in desert regions.* The principal characteristic of desert pans is their hardness. They are cemented into a solid mass which retains its firmness when wet and may require blasting to break. These pans vary in thickness from less than a foot to several feet in one solid layer. Several thin cemented strata may exist interleaved with loose friable material. Zones of cementation of this type are characteristic

of desert soils and are found in varying stages of development in practically all but the freshest desert soils.

*b. Laterite.* Laterite is a residual soil formed when ground waters remove certain constituents of the original soil. In areas of high rainfall where some soils are subjected to the leaching action of ground water over long periods of time, certain silicate constituents may be largely removed by solution, the more insoluble residues remaining. These residues consist of either the hydrated oxides of iron, the hydrated oxides of aluminum, or any combination of these with minor quantities of other minerals. A soil so formed is known as *laterite.* It is referred to as ferruginous, aluminous, or a mixture of these, depending on the character of the parent material. The hardened ferruginous type is known as *ironstone,* which is usually a shade of red. The aluminous type is known as a *bauxite,* which is usually brown, gray, or white.

## Section III. MASS MOVEMENT OF THE MANTLE AND ITS PART IN EROSION

### 23. General

Although a less active agent of erosion than are water, wind, and ice, gravity is responsible for large mass movements of the earth's mantle. For the most part the movement is slow, but it may be locally rapid or even catastrophic. This section presents the different types of mass movement that can be attributed wholly or in part to the force of gravity, and describes briefly the conditions under which movement is initiated.

### 24. Slow Flowage or Movement

*a. Soil Creep.*

(1) The mantle on even the gentlest surface moves slowly down the slope, the movement being detectable only by such things as tilted and dislocated telephone poles, trees, fences, road beds, and railroad grades (fig. 30). This process, known as *soil creep,* occurs primarily in the weathered soil above bedrock, and the motivating force is gravity, acting on material only partially saturated with ground water.

(2) In regions having cold winters, each freezing of the contained water in the soil lifts the soil in a direction perpendicular to the slope; each thawing drops the material downward perpendicular to the horizontal. As a result of repeated freezing and thawing, the soil moves a considerable distance down the slope.

*Figure 30. Soil creep. Near Coal Creek, Yukon River, Eastern Alaska.*

*b. Solifluction. Solifluction,* as used in this manual, refers to a special type of soil creep common in *permafrost* regions, or regions where the subsoil remains permanently frozen. Meltwater formed during the warm seasons has no opportunity to drain downward through the permafrost layer. The excess water saturates the mantle. On slopes this saturated mantle moves as a viscous liquid downhill over the frozen subsoil. This condition exists in vast areas of northern Canada, Alaska, Siberia (fig. 132) and Russia.

*c. Rock Creep.* This slow movement of consolidated material recently detached from bedrock outcropping along a slope is referred to as *rock creep.* In massive formations, blocks produced by fracturing slowly move away from the parent material and eventually assume the angle of the sloping surface. In thin-bedded rocks that are steeply inclined with the surface slope, the movement of the surface material bends the strata downslope to such an extent that the bedding planes may show a false dip.

## 25. Rapid Flowage and Movement

*a. Mudflows.* Fine rock debris that collects on steep slopes in arid and semiarid regions becomes water-soaked during heavy rains and flows down the slope in much the same manner as running water. This viscous mass of muddy debris is called a *mudflow.* Movement is usually much faster than solifluction, and generally follows stream channels to the piedmont slope where the mass spreads out into a wide sheet. The mass builds up tremendous momentum capable of carrying huge boulders for considerable distances.

*b. Landslides.*

(1) In regions of extremely rugged terrain, large masses of soil and rock may break loose and move down the slopes, sometimes slowly but usually very rapidly, picking up other material in their descent and causing complete destruction of everything in their path. This phenomenon is called a *landslide* (figs. 31 and 32). Whereas creep operates almost entirely within the soil layers, landslides often include large amounts of the underlying bedrock. Conditions favoring landslides are found in rugged regions of steeply dipping beds where ground water has the opportunity to percolate along the joint and bedding planes, thus weakening the rock to the extent that it finally breaks away from the parent material.

(2) Rock debris accumulating in large quantities at the bases of steep mountain fronts may, where slope conditions are favorable, take the form of a "stream" moving slowly down the valley. This type of landslide is called a *rock glacier.* Gravity, which is the moving force, is aided considerably by the alternating freezing and thawing of the water held by the rock material.

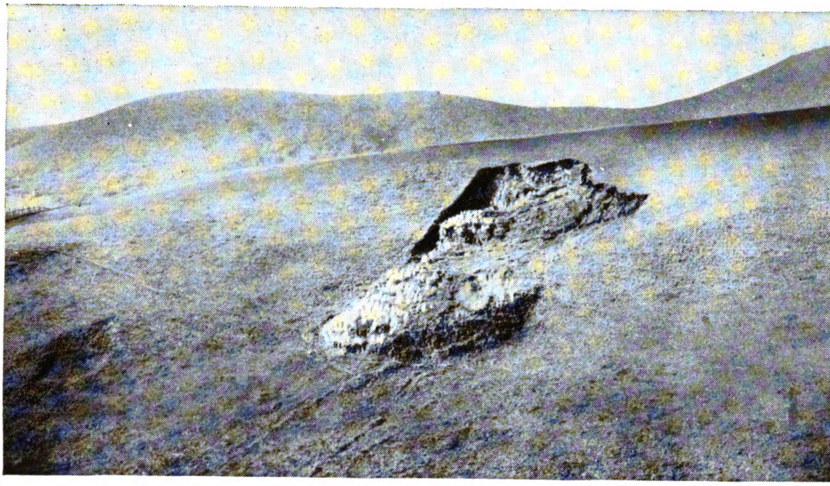

*Figure 31. Landslide.*

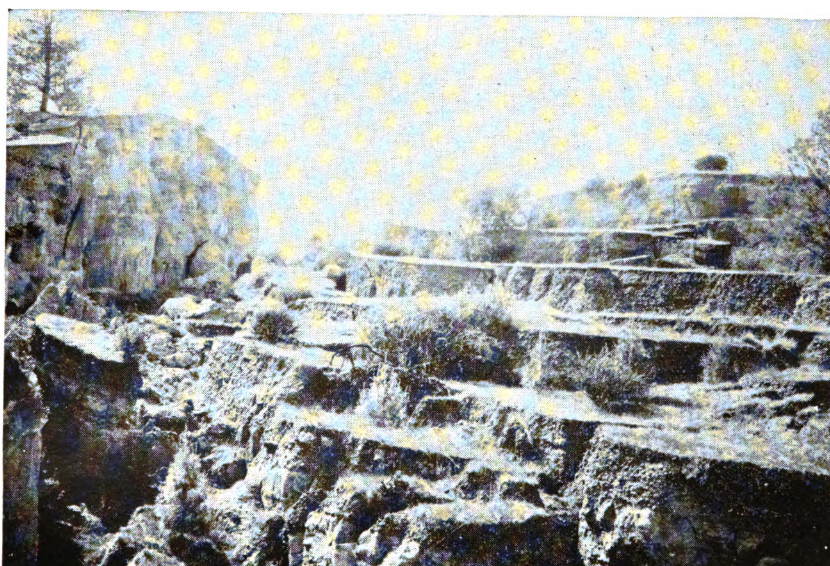

*Figure 32. Step-faulting in weakly consolidated gravel and sand resulting from landslip or slump. The step or bench surfaces were originally at the same general elevation.*

(3) The lateral migration of bends in streams is commonly accompanied by *slumping*, the adjustment caused by the removal of sandy sediments from beneath the more cohesive top stratum in the cut bank (par. 27*b*). Bank recession by slumping causes the subsidence and bankward tilting of bank sediments in blocks or large masses, the size of the slump block varying directly with the thickness of the top stratum. After the mass slides into the river channel, the slumped block is quickly removed by the action of the water.

## Section IV. EROSIONAL AND DEPOSITIONAL TOPOGRAPHIC FEATURES PRODUCED BY STREAMS, OCEANS, GLACIERS, WIND, AND SUBSURFACE WATER

### 26. General

*a.* The tendency of streams, oceans, glaciers, wind, and subsurface water to waste the land by gnawing at its surface and, sooner or later, to carry away practically all the loosened substance and deposit it some distance from its starting point, produces most of the relief features on the surface of the earth. These features include the *erosional forms,* such as valleys, produced principally by the abrasive action of the agent and its load of rock particles; the *residual forms,* such as peaks, which are remnants of the former landmass; and the *depositional forms,* such as sand dunes, produced when the load is released from the transporting agency. These in turn, particularly the residual forms, are modified by climatic conditions which control the weathering processes that may operate in the region (figs. 33 and 34). In general, however, many of the topographic forms can be readily classified according to the agent of erosion which produced them. Conversely, certain relief forms can be anticipated when the major erosional agency is recognized in the field. Recognition of either the topographic forms or the erosional agency is extremely helpful to the military engineer in locating construction material.

*b.* This section describes the erosional and depositional forms attributed to streams, oceans, glaciers, wind, and subsurface water, and helps in their field recognition.

## 27. Streams

*a. Factors in Stream Erosion and Deposition.*

(1) *Stream flow.* A stream with its load of sand and gravel acting as an abrasive is able to cut into highly consolidated rock. The speed of cutting is largely dependent on the *velocity* or speed of the stream; the velocity, in turn, is dependent on the slope or *gradient* and the cross-sectional area of the channel and on the volume of water. The amount of sediment and the size of the fragments a stream can carry as suspended load, or force along its channel as bottom load,

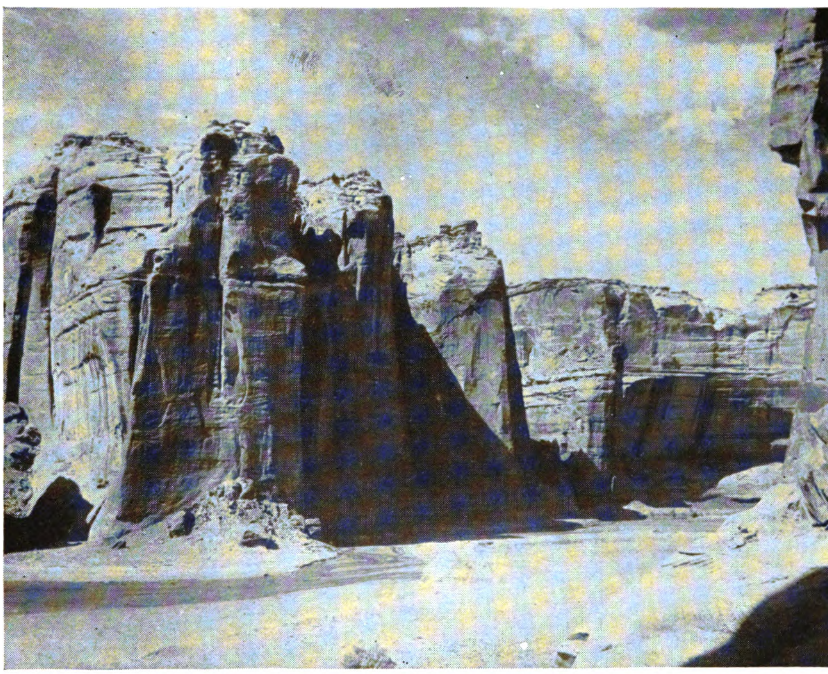

*Figure 33. Topographic expression of rock weathered in arid regions. Canyon de Chelly, Arizona. (Compare with figure 34).*

are also largely dependent on the velocity of the stream.

(2) *Adjustment of channel and load to velocity.* A stream loaded with sediment is continually picking up material in one place and dropping it in another because of the change in the

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velocities of the currents. Sand and gravel bars form wherever the gradient becomes low and persist until a change in the currents leads to their removal. Generally only minor changes in the position of bars occur as long as a stream is at low water, since at any point a rough equilibrium is established between material eroded and material deposited. However, this equilibrium is disrupted when a stream is in flood. The increased discharge of water increases the velocity of the stream, and hence increases the abrasive power, capacity, and over-all cross-sectional area of the channel. Part of this

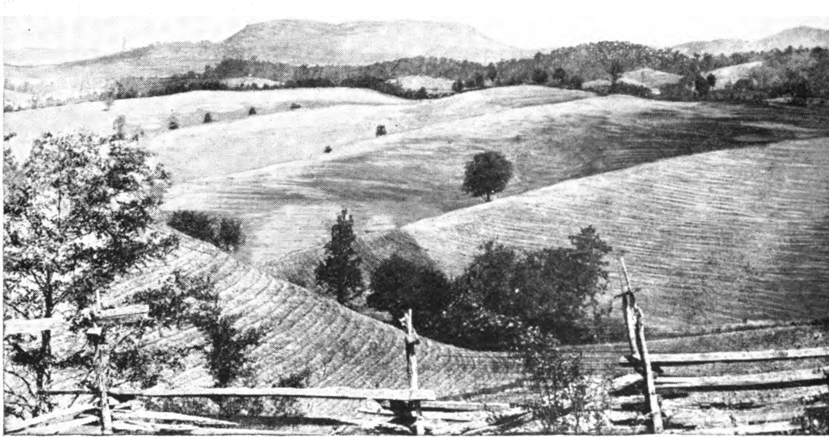

*Figure 34. Topographic expression of rock weathered in humid regions. Near Luray, Virginia. (Compare with figure 33).*

increase in size is expressed in a deepening or *degrading* of the channel as much as two to three times the amount of rise in the water level of the stream. As the flood subsides the channel *aggrades* or refills with sediment as the velocity decreases. These seasonal flood and low-water stages with their accompanying changes in the shape and cross section of the river channel constitute the stream *regimen* (fig. 35). A stream's regimen is then the normal behavior of the stream throughout each year.

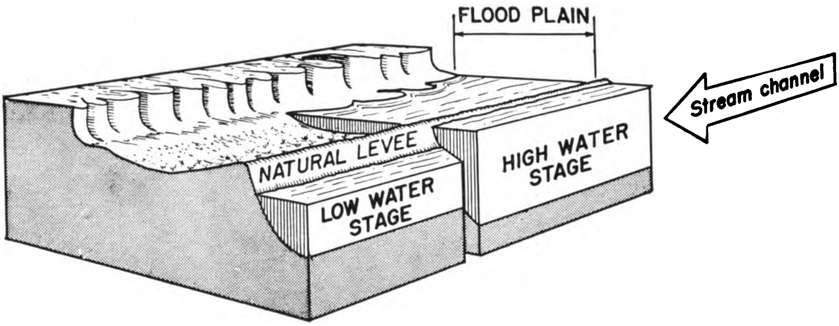


*Figure 35. Adjustment of channel and load to discharge.*

(3) *Adjustment of channel and load to slope.* Closely related to change in slope is a corresponding change in load. During the early stage of valley aggradation, the large volume of coarse sediments cause an overloading of the streams, the discharge being maintained in numerous, shallow, constantly flooding, *braided channels* (fig. 118). When the gradient of the stream becomes sufficiently reduced so that the dominant introduced load is fine sands, silts, and clay, the discharge is concentrated in a single channel, that most commonly develops into a *meandering channel* (fig. 117).

(4) *Base level.* A stream will continue downcutting its channel as long as its gradient is steep enough to give the stream the required velocity for erosion and transportation of the eroded material. When the gradient of a stream coincides with sea level, the eroding and transporting power of the stream is reduced to nothing. Sea level projected inland represents the lowest level to which a stream can erode its channel and is the *base level* of stream erosion (fig. 36). Where a stream empties into a lake, the level of the lake projected inland is the local base level of erosion for the drainage basins which lie upstream.

(5) *Ferrel's law.* Some rivers, especially those at high latitudes, are subject to *Ferrel's law.* Ferrel's law applies to the effect the earth's rotation has on moving bodies, causing the bodies to deflect from a straight path. The deflection is to the right in the Northern Hemisphere, and to the left in the Southern Hemisphere. Aside from other factors influencing

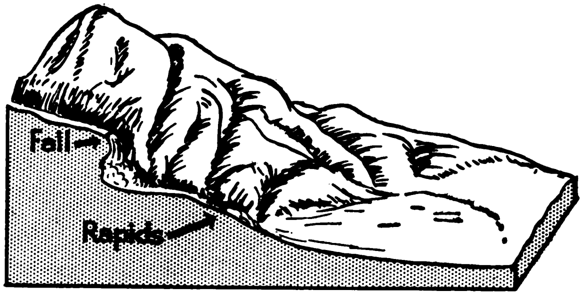


*Figure 36. Longitudinal profile through a stream channel.*

the shape of a stream valley, rivers in the Northern Hemisphere have a tendency to cut into the right side of their valleys. The Yukon River of Alaska has more bluffs on the right side of the valley and the widest floodplain on the left side; driftwood collects almost entirely on the right bank. In southern Long Island the many small streams flow in little valleys that have steep right (west) walls and gentle left slopes. Similar conditions have been observed on the Missouri River, on other rivers in Alaska, in northern Siberia, in southern France, and elsewhere.

(6) *Fluviatile cycle of erosion.*

(*a*) The stages through which a land mass evolves from the time it is uplifted until the region is completely reduced to base level constitutes a *geomorphic cycle.* A geomorphic cycle may be accomplished by any of the erosional processes. The cycle controlled by streams and associated processes in the enlarging of the valley walls (*b*(1) below), known as the *fluviatile cycle,* is the most important of these geomorphic cycles.

(*b*) The stages of development are referred to as youth, maturity, and old age. A plain, newly raised from the sea to a height above sea level, is at once attacked by erosion processes (youth). Streams cut gulleys, then deepen and widen them until no flat land remains; the whole surface becomes canyons and sharp divides. This is the stage of greatest ruggedness and relief (early maturity). Gradually the streams further widen their valleys at the expense of the divides, eventually developing floodplains in valley

bottoms. The divides waste away and become less sharp in form. This stage (late maturity) is characterized by rolling hills and broad valleys. Finally the surface becomes low and flat, developing a terrestrial *peneplain* (old age). Isolated areas of resistant rock rising above the general level of the peneplain are called *monadnocks.*

(*c*) If, before the land can be completely worn down, forces from within the earth raise it again, a new erosion cycle begins. Endless interplay between leveling forces at the surface and elevating forces inside the earth has produced the varied landscape on the face of the earth.

*b. Erosional Features.*

(1) *Valleys.* The most conspicuous erosional feature produced by a stream is its valley. A valley starts as an irregularity in a new land surface, which develops into a gully and finally into a valley that is lengthened by *headward erosion* and deepened by stream action. In moderately rugged country, a stream cuts principally downward into its bed. If the stream cuts through rock, the resulting valley may be a gorge with nearly vertical walls. In most unconsolidated materials, however, vertical walls do not remain, but recede as the stream cuts deeper. The widening or wearing back of the valley sides is known as *lateral erosion.* It is caused partly by a slumping of material along the *concave bank* (fig. 37) which has been undermined and partly by other processes, such as slopewash, landslides, and creep, that act directly on the slopes.

(2) *Valley patterns* (figs. 38 and 39). Valley or drainage patterns can be grouped into at least five basic patterns: *dendritic, trellis, radial, annular,* and *rectangular.* In general, these patterns are controlled or influenced by the underlying geologic structure of the area. Although the individual patterns produced by the conditions indicated below are subject to considerable variation, they may be used to determine the nature of the underlying structure in unknown areas where similar valley or drainage patterns exist.

(*a*) Flay-lying rocks and areas of generally impervious soils create a dendritic pattern.

(*b*) Streams in fold mountains follow lowlands and receive right-angled tributaries from adjacent ridges. This forms

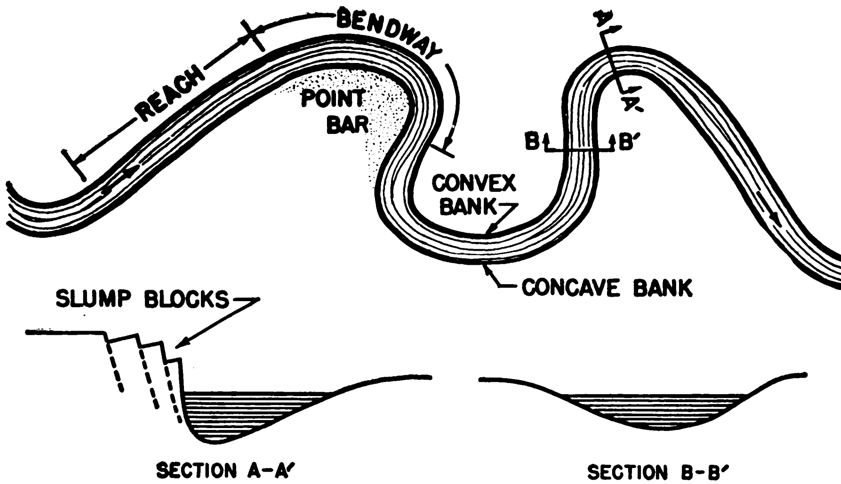


*Figure 37. Nomenclature and profile characteristics of a meandering stream.*

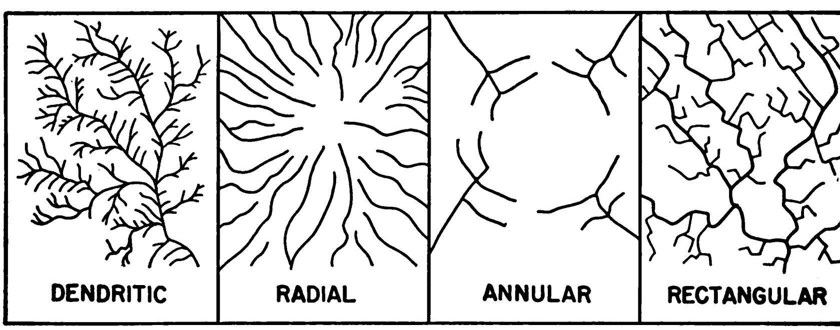


*Figure 38. Valley patterns.*

the distinctive trellis drainage pattern exhibited by western Virginia (fig. 39). The main streams which cut across the ridges form *water gaps* (fig. 40). Former water gaps no longer occupied by the streams which cut them are called *wind gaps*.

(*c*) A radial drainage pattern occurs in areas having a prominent peak or dome with the drainage features radiating outward from a central point or area.

(*d*) Annular drainage patterns are developed in connection with certain igneous and sedimentary material when

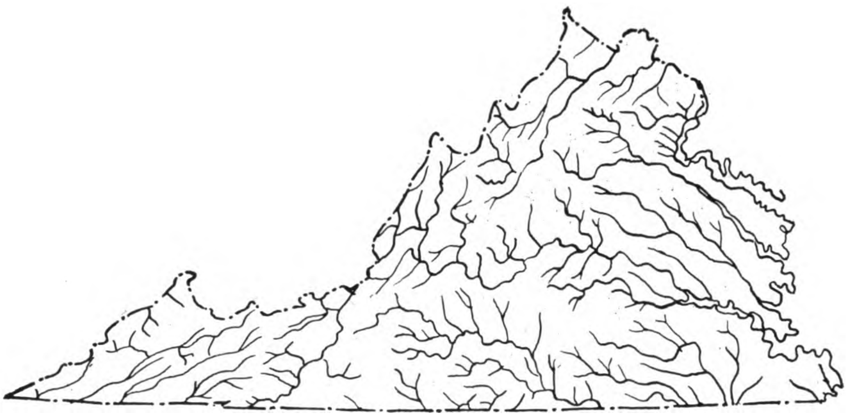

*Figure 39. Map showing stream patterns in Virginia.*

associated with domes (pars. 44–48).

(*e*) Rectangular drainage patterns indicate angularity produced by rock joints or changes in rock materials for flat-lying rocks.

*c. Depositional Features.*

(1) *Channel deposits.*

(*a*) In the *reaches* or straight sections of a stream between bends, *bars* or *shoals* are commonly formed. They consist of various grades of sediment depending on the transporting capacity of the stream. They are rarely permanent features, being moved from one position to another within the channel as stream conditions change.

*Figure 40. Delaware Water Gap. Northwestern New Jersey.*

(*b*) When the stream current is deflected against the concave bank, slack water is created along the *convex bank* or *point* (fig. 37). This decrease in velocity provides, in many cases, favorable conditions for deposition of sand and gravel and the formation of the *point bar* (fig. 37).

(2) *Alluvial fans.* Where a stream emerges from a steep slope onto a flat plain, its velocity is immediately checked and deposition of the stream's load takes place at the point where the stream enters the plain. These deposits, called *alluvial fans* (fig. 41) have the shape of a low cone with the apex of the cone pointing upstream. As figure 41 illustrates, alluvial fans are conspicuous in arid and semiarid regions. They also occur in humid regions where there is an abrupt change in the gradient of tributaries where they enter the wide valleys of master streams.

(3) *Alluvial plains.* Where the net result of stream activity is deposition, the deposited stream-borne material builds up the valley bottoms and forms *alluvial plains* extending from valley wall to valley wall (figs. 19 and 42). The alluvial plain, therefore, includes both the *floodplain,* or area adjacent to the stream subject to seasonal flooding, and dissected alluvial plains and fans not completely covered by flood water. Only those streams that occupy their entire valley bottoms lack alluvial plains or floodplains (fig. 43). Where streams have cut broad valleys, these alluvial plains may be many miles wide, forming extensive flats across which the streams meander, shifting their channels gradually from one side of the valley to the other. As streams shift, old channels are left behind as sloughs or bayous and as curved lakes called *oxbow lakes* (fig. 117).

(4) *Natural levees.* A widespread top stratum deposit characteristic of floodplains is the *natural levee* (fig. 35). It consists of a ridgelike mass of silts, silty sands, and silty clays laid down by overbank flow along stream channels. The deposits are thickest and coarsest at their crests along the riverbank. They thin rapidly and become finer away from the river where they merge with the *backswamp* deposits of thinly laminated, silty clays and clays which lie in the flood basin beyond the natural levees (fig. 35).

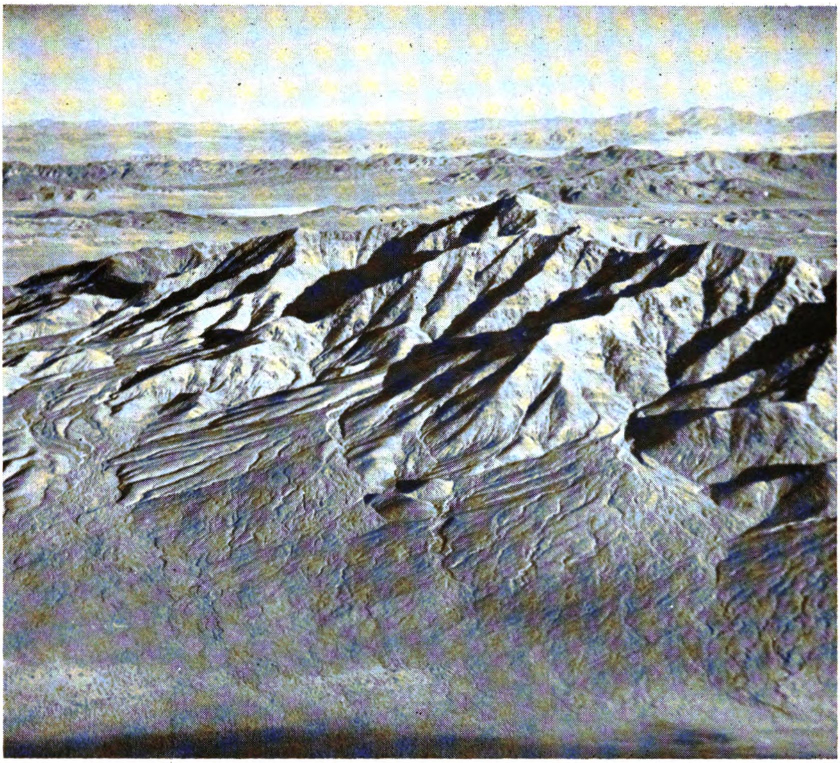

*Figure 41. Alluvial fans at base of mountains.*

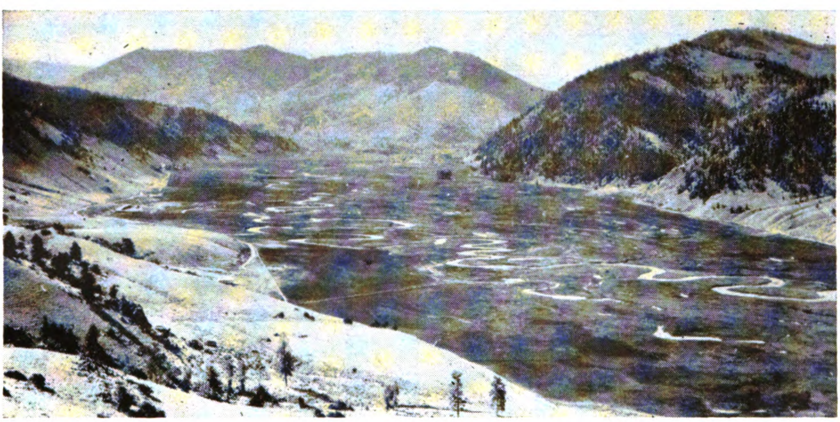

*Figure 42. Small alluvial valley in mountainous terrain. Cebolla Creek, California.*

(5) *River terraces.* When changing conditions cause streams to deepen their valleys, remnants of the alluvial plain may remain on the slopes of the valleys above the new river level. Such isolated flat surfaces arranged in steplike platforms separated by steeper slopes are called *river terraces.* They may be composed entirely of stream gravel as shown in figure 44; or, as in the case of the depositional terraces along the

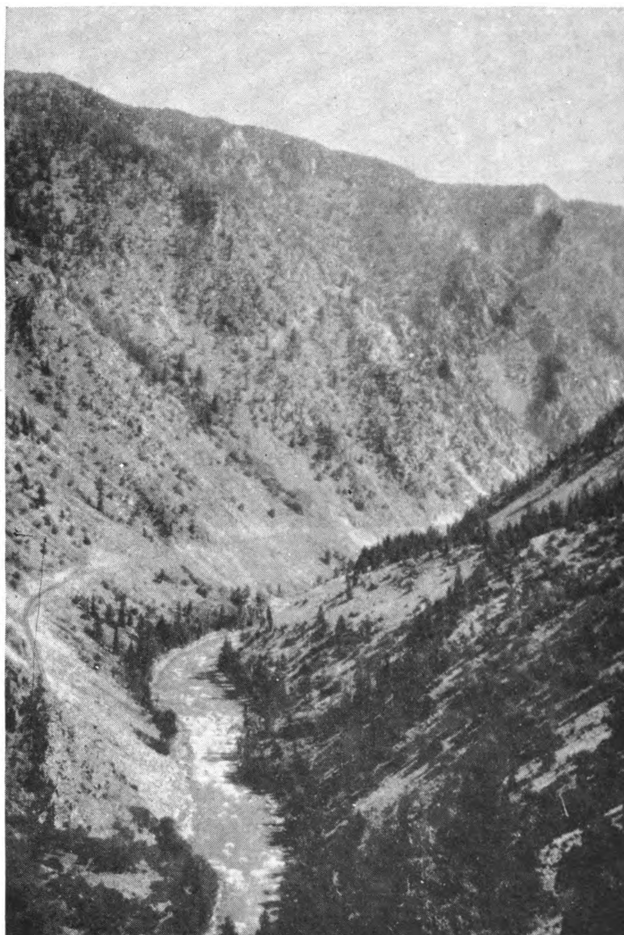

*Figure 43. Stream valley in rugged country showing the absence of an alluvial plain and the characteristic V-shape. Yellowstone River, Yellowstone National Park, Wyoming.*

Mississippi River, each terrace may be composed of material that grades from a graveliferous sandy layer at the bottom to silts and clays at the top (fig. 19).

(6) *Delta plains* (fig. 45).

(*a*) Where streams flow into bodies of water such as lakes or the sea, the current velocities are abruptly checked, and the sediments which the streams have been transporting are consequently dropped. If not washed away by waves and currents, these sediments accumulate to form *deltas*

*Figure 44. River terraces. Santiago Creek, San Joaquin Valley, California.*

*Figure 45. Typical small lobate river delta.*

which are gradually built up slightly above the level of the water body into low, generally marshy plains or *delta plains.* The upstream limit is regarded as either the point where *distributary streams* that carry sediment to the outer portion of the delta begin to branch from the main stream, or as the upstream limit of the land reclaimed from the lake or sea by deposition of stream sediments. The two limits rarely coincide, but both are convenient for purposes of description.

(*b*) The surface of a delta plain usually is a network of distributaries and levees, with wide lakes and marshes between stream channels. They are underlain by unconsolidated alluvium consisting of clay, silt, and fine sand; gravel in large quantities is uncommon.

## 28. Oceans

*a. Factors in Marine Erosion and Deposition.* Waves, currents, and tides, the basic types of water movement in oceans, interact to produce the erosional and depositional features which can be observed along coastlines. By far the most important of these are waves, as an agent of erosion, and longshore currents, as an agent of deposition.

(1) *Waves.* Waves are generally caused by winds blowing along the surface of the water body. They are of two types:

(*a*) *Oscillatory waves* are those in which there is little or no advancement of the water particles with the movement of the wave form. Normally, they do not extend to the coastline and, therefore, do not perform much erosion.

(*b*) *Translatory waves* form as the oscillatory waves move from deep to shallow water. From this breakerline, the water particles move landward with the wave form, and the wave crest rises above the general water level. They are characteristic of coastal areas and are the active agent of marine erosion. It has been estimated that the average dynamic impact of translatory waves off the coast of Scotland in winter is slightly more than 2000 pounds per square foot.

(2) *Currents.* Of the numerous varieties of currents that move the water in oceans, those of particular engineering significance are tidal currents, undertow, and longshore currents. All of these, at least locally, modify the shore zone and, in

some manner, are responsible for many of the conspicuous topographic features of coastlines.

(*a*) *Tidal currents.* The rise and fall of the sea in response to the tides (produced by the gravitational attraction of the sun and moon) varies from a few inches at the heads of long embayments to as much as 50 feet in some narrow estuaries. This mass of water, moving in and out of estuaries, bays, streams, and other irregularities in the coastline, sets up *tidal currents* that effectively transport large quantities of sediment and perform a limited amount of erosion through scour.

(*b*) *Undertow.* Water forced on the beach by waves finds its escape along the bottom in a direction more or less perpendicular to the shore. This broad outflowing current is called an *undertow.* On steep beaches, the undertow may have sufficient velocity to move material from the beach and deposit a large percent in the deeper water offshore.

(*c*) *Longshore currents.* Where waves strike the beach at an angle, a force component moving in a direction parallel to the beach sets up a current which moves more or less parallel to the shoreline. These currents are called *longshore currents.* Along many coasts, they are very effective agents of transportation and deposition.

*b. Erosional Features* (fig. 46).

(1) *Cliffs.* Escarpments or *cliffs* ranging from a few feet to hundreds of feet in height are universally present along coastlines. These conspicuous features have resulted from the dynamic impact of the waves dashing against the land. Slow recession inland is the result of continued wave action, augmented by the abrasive action of material removed from the cliff by undermining its base and material brought in from elsewhere along the shore.

(2) *Wave-cut bench.* As the cliff retreats inland, it leaves behind a *wave-cut bench* or platform, the inner margin of which is exposed at low tide. The action of the water flowing back and forth across the bench, combined with the abrasive action of the rock debris, gradually lowers the bench and allows the waves to concentrate their action on newer portions of the platform.

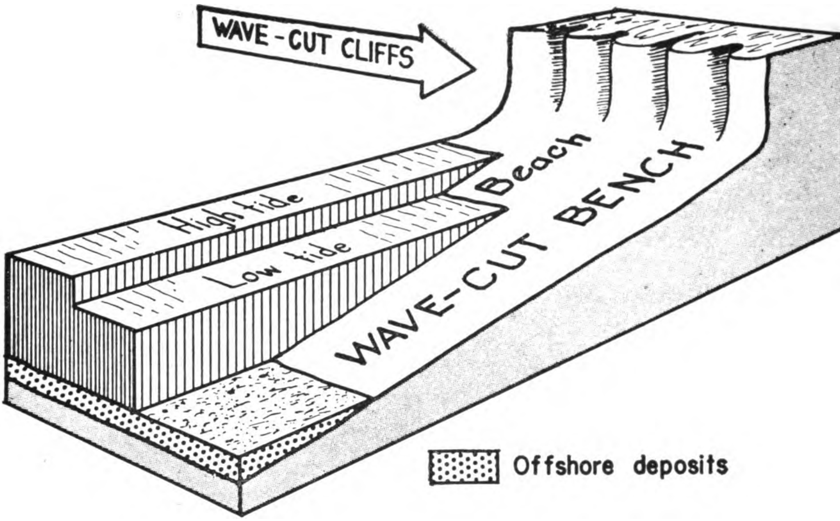


*Figure 46. Wave-cut cliff and bench.*

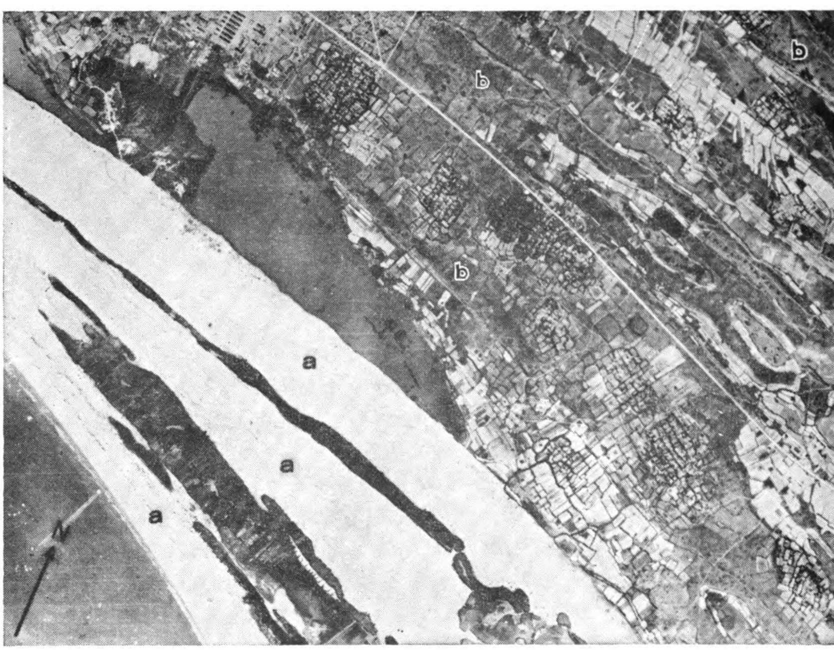


*Figure 47. Coast with beach ridges. Hainan Island, China. a, ridges of loose sand. b, older ridges covered with vegetation.*

*c. Depositional Features.*

(1) *Beaches and beach ridges.* The narrow zone which lies between the low water line and the upper limits of high water constitutes the *beach.* It is composed of wave-worn debris, commonly sand, gravel, or shell, depending on the kind of material available in the area, the strength of the waves, and the distance or time the material has been in transit. *Beach ridges,* or ridgelike masses of beach material on the upper part of the shore, are often stranded inland where the shoreline is advancing seaward (fig. 47). Such features along the coast of Louisiana are referred to as *cheniers.*

(2) *Barrier or offshore bars.* On gently sloping coasts, sediment dislodged by large waves as they move toward the land is deposited at the breaker line (fig. 48). Through accretion, this sediment is gradually built up above sea level, forming *barrier or offshore bars* (fig. 49) that roughly parallel the shoreline. Such features are notably developed along many sections of the Gulf of Mexico coast (fig. 48), and down the Atlantic coast from New Jersey to Florida.

(3) *Spits and bars* (fig. 50). Sediment-laden longshore currents build many deposits in the deeper water of bays and other curvatures in the shoreline where the velocity of the current is checked. A deposit with one end attached to the mainland is called a *spit.* Spits built across the entrance of a bay and more or less completely blocking the inlet form a topographic feature referred to as a *baymouth bar,* or simply a *bar.*

(4) *Coral deposits. Corals* are marine animals which secrete protective and supporting structures composed chiefly of calcium carbonate. Their habitat is tropical ocean water, usually at a depth of less than 100 feet, and with a temperature range of from 64° F. to 80° F. In their early stages of development they move about freely, but in the adult stage they adhere to a fixed base and form colonies. These colonies develop along the beaches or offshore from the beach and form *fringing reefs* (fig. 51). Fringing reefs are composed mostly of the protecting and supporting structures of dead colonies with a surficial coating of living colonies and coralline algae. Sediment consisting principally of coral fragments, but including the remains of other animals and plants which inhabit the same environment (foraminiferal

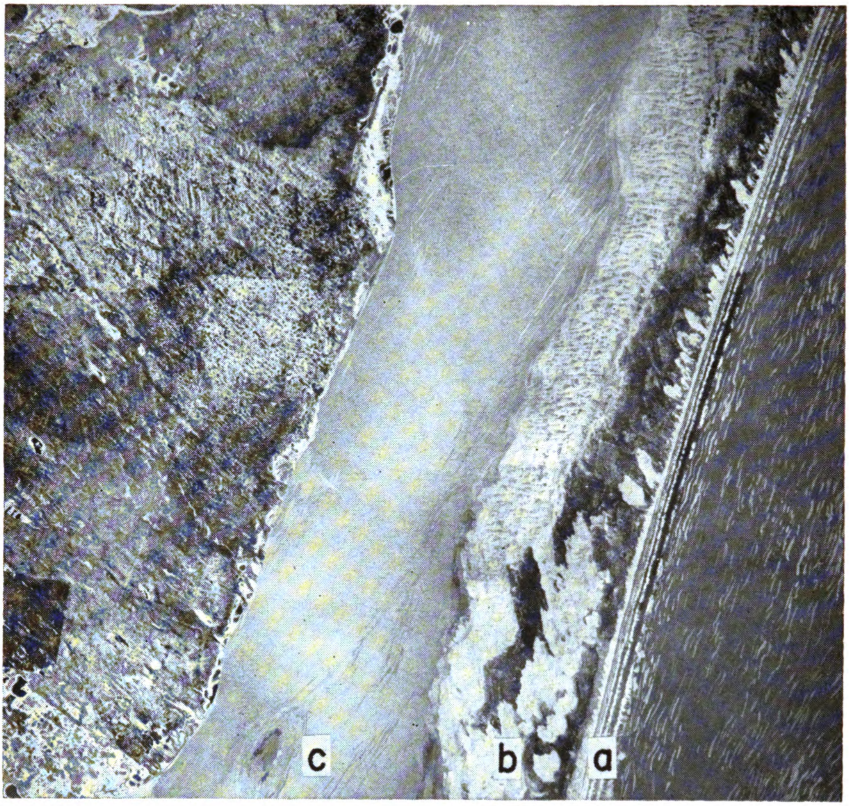


*Figure 48. Breaker line paralleling offshore bar, Kleberg County, Texas. a, Breaker line, b, Offshore bar. c, Lagoon.*

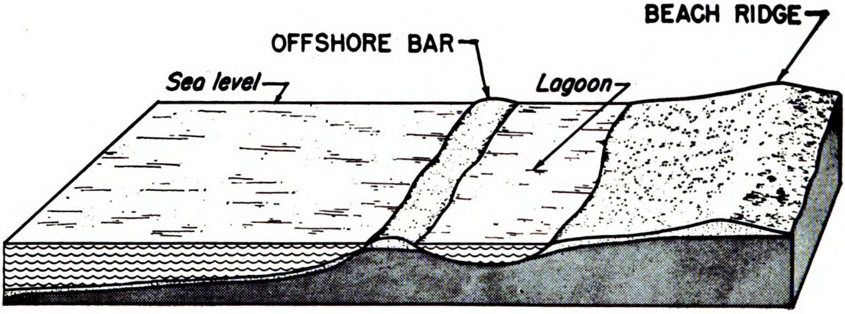


*Figure 49. Offshore bar and lagoon.*

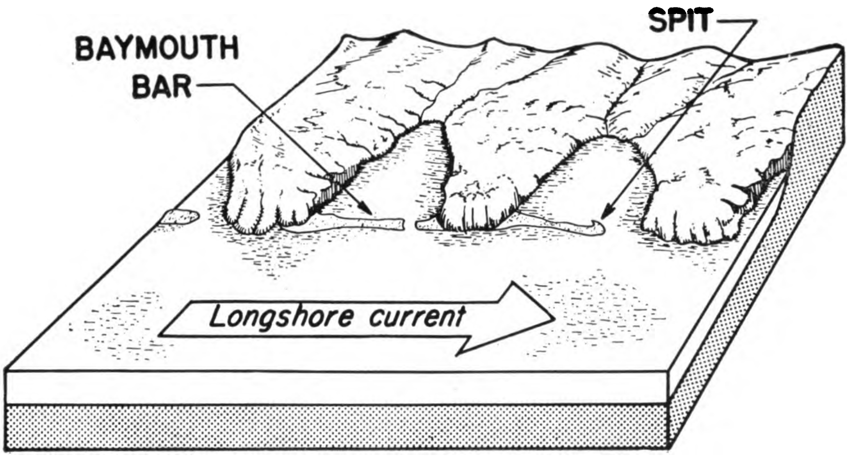


*Figure 50. Spits and bars.*

shells, clam shells, coralline algae, and the like), is transported by the waves and currents and deposited on the beach. This sediment produces the normal marine depositional forms described in (1), (2), and (3) above.

## 29. Glaciers

*a. Types.* Glaciers are masses of snow and ice which, under the influence of gravity, slowly move out over the land from the snowfields where they originate. They are classified on the basis of mode of occurrence into two types:

(1) *Valley or mountain glaciers* (fig. 52) are those streams of ice that flow down mountain valleys from snowfields that form in the high peaks. When they extend to the plain at the foot of a mountain range, they may merge to form ice masses called *piedmont glaciers.*

(2) *Ice sheets or continental glaciers,* so named because of their great areal extent, are usually formed at lower altitudes than valley glaciers. These tremendous masses of ice, moving slowly over thousands of square miles of land, were once prevalent in both hemispheres. In Pleistocene time, for example, a great ice sheet spread out over most of Canada and a large part of north central United States (fig. 53), causing widespread modifications of the preglacial topography.

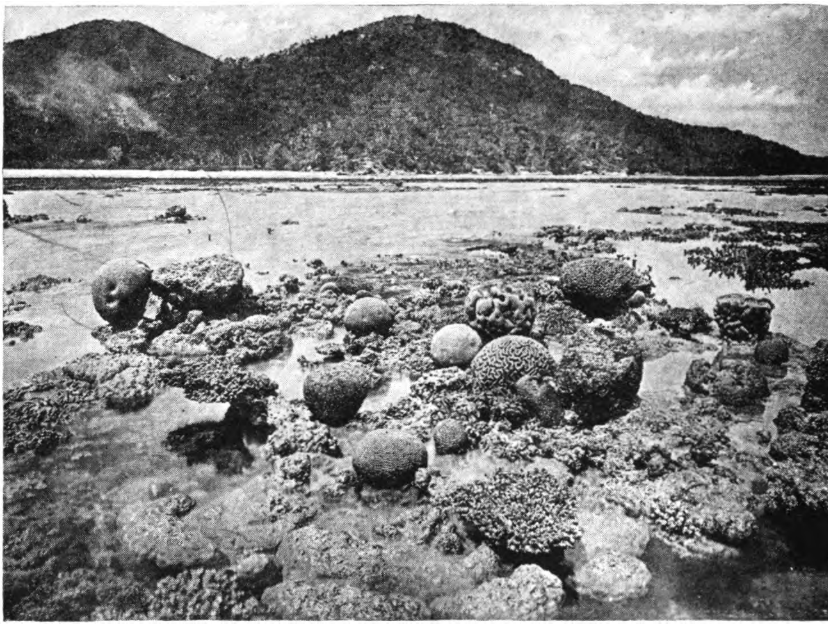

*Figure 51. Fringing coral reef. "Great Barrier Reef," Australia.*

*b. Factors in Glacial Erosion and Deposition.*

(1) *Erosion.*

(*a*) The active processes of erosion are *plucking,* or *quarrying,* and *abrasion.* Plucking or quarrying is accomplished by frost wedging (par. 20*a*(1)) or by pressure of the ice breaking off blocks of unsupported rock. This loosened or partly loosened debris is then picked up and incorporated into the moving ice. Abrasion is accomplished with the rock fragments which are frozen in or pushed along the base of the ice mass. The intensity of this scouring action of glaciers is reflected in the depth of the *grooves* or *striae* (fig. 54) cut into the bedrock traversed.

(*b*) Valley glaciers generally acquire very large loads since they have not only material derived by plucking and abrasion at the base of the glacier but also material which has fallen on the surface of the ice from the mountain slopes above. Ice sheets or continental glaciers acquire

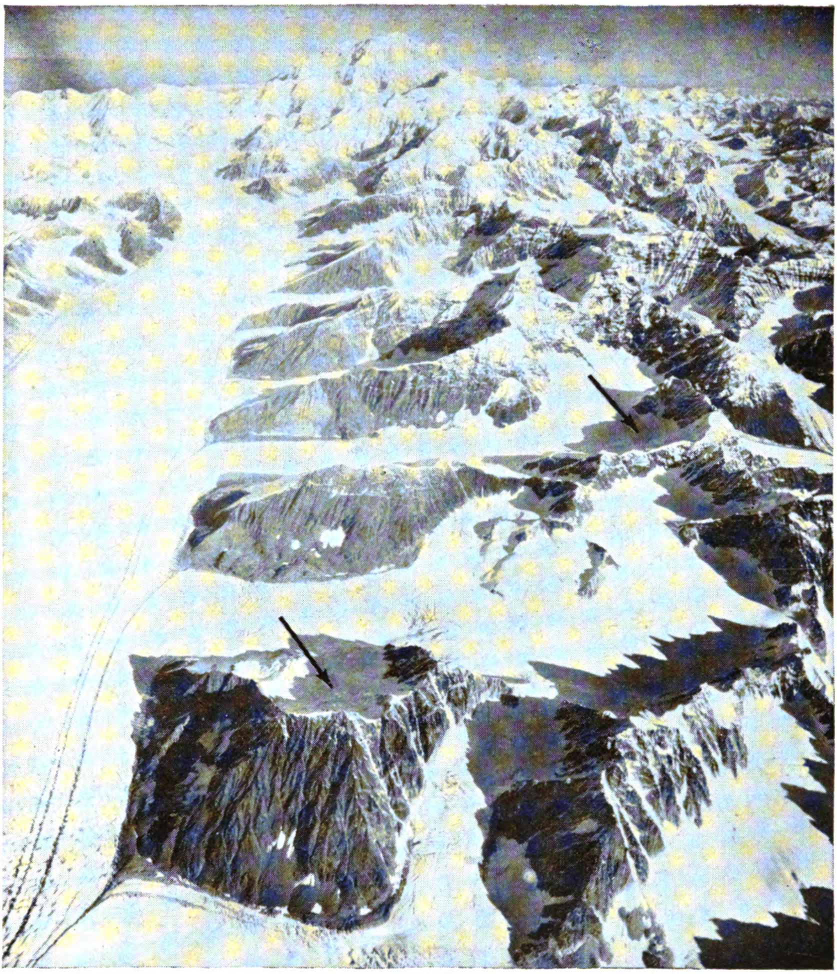

*Figure 52. Valley glacier system: main glacier at left, feeders entering from right. Kahiltna Glacier, Alaska. Arrows point to cirques.*

most of their load by plucking or quarrying material from the surface over which they move.

(2) *Deposition.* With the exception of that sediment deposited beneath the glacier and overridden by the advancing ice, most of the material carried by glaciers is deposited near the place the ice melts. Part of this load is deposited directly by the ice; the remainder is further transported, sorted, and

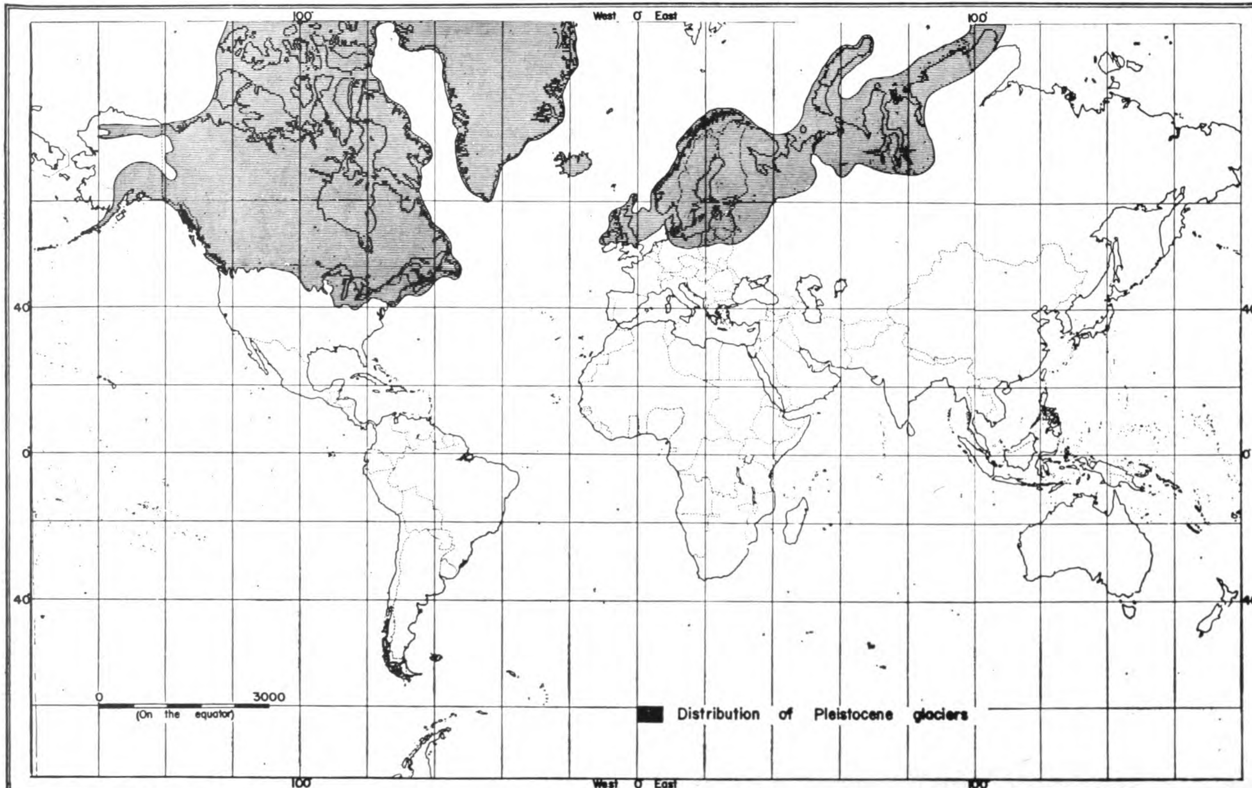


*Figure 53. World-wide distribution of Pleistocene glaciers.*

deposited by meltwater flowing in channels that form on, in, or beneath the ice. Thus the topographic features resulting from deposition by glaciers contain sediment with varying degrees of water assortment in the stratified drift deposits, and varying assemblages of material in the unstratified drift or till.

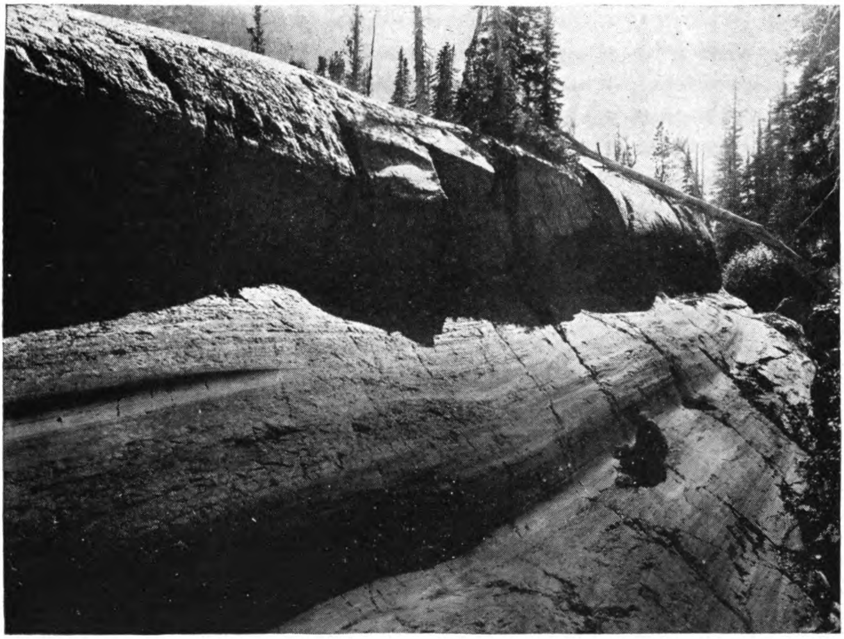

*Figure 54. Grooves cut by continental glaciers in rock. Glacier Creek, Flathead National Forest.*

c. *Erosional and Residual Features.*

(1) *Cirques.* The extreme headward portion of many glaciated valleys is blunt and steepened, commonly with a semicircular shape much like a half a bowl. These features are called *cirques* (fig. 52). They are formed by the plucking, quarrying, and abrading action of the glacier as it moves down and out of the mountain peaks, assisted by the diurnal freezing and thawing of meltwater in niches and fractures in the rock.

(2) *Col.* Where two cirques intersect each other from opposite sides of a divide, a low pass is formed called a *col* or *saddle.*

(3) *Horn.* Where three or more cirques merge, the residual pyramidal peak is called a *horn.* The famous Matterhorn of the Swiss Alps is a typical example of this feature.

(4) *U-shaped valleys.* Glaciers, though capable of flowing, are relatively inflexible and, therefore, do not conform easily to the irregularities of the mountain valleys which they occupy. Consequently, the glacier grinds against the mountain spurs that project into the valley, beveling them into broad facets. It gouges and rounds out the narrow, V-shaped stream valleys. The result is a broad, steep-walled *U-shaped valley* through which the glacier can move with a maximum of speed and a minimum of effort (fig. 55).

(5) *Hanging valleys.* Under normal conditions of valley development by streams, tributaries enter the main stream valley at the same level as the main stream. In the case of glaciers, however, the main glacial valley is deepened to a greater extent than the valleys of the tributary glaciers, because of the greater volume of ice in the main trunk glacier as compared to that in the weaker lateral feeders. After the ice melts *hanging tributary valleys* are left. They enter the main valley at some height above the floor and, when occupied by a stream, create a waterfall. Yosemite alley in California contains many typical examples.

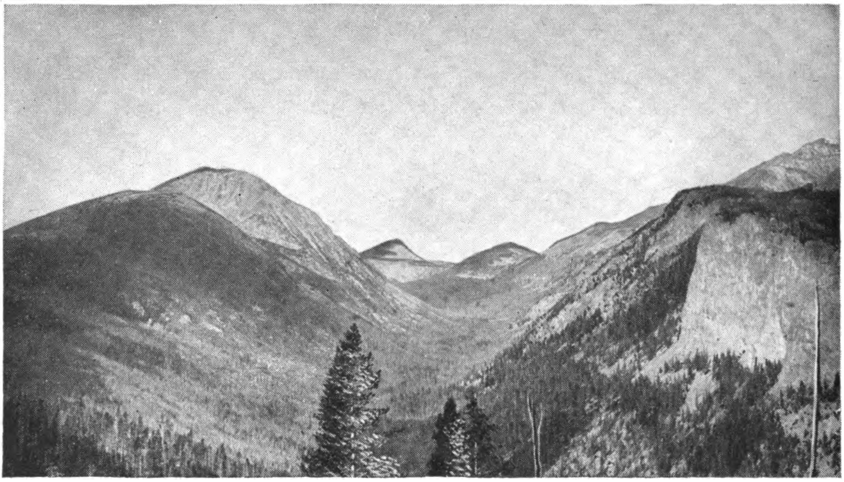

*Figure 55. U-shaped valley formed from a valley enlarged and modified by a former glacier. Yosemite National Park.*

*d. Depositional Features.*

(1) *Moraines.* Moraines consist of debris that was once carried in and on the ice (fig. 56) and then left by the glacier upon melting (fig. 57). Moraines at the end of a glacier are called terminal, those at the sides lateral, and those resulting from mass melting of ice in place form blankets called *ground moraines.* The glacial debris in moraines is normally poorly sorted and not in layers, with all sizes of sediment from large angular boulders to fine clay indiscriminately mixed.

(2) *Eskers.* Streams flowing in tunnels or fissures under a glacier are often supplied with so much material that they may block their own channels with coarse debris such as sand and gravel. If the ice under which the stream flowed melts without moving, the deposits in the stream appear as a long, sinuous, symmetrical ridge extending in a direction roughly parallel to the direction of movement of the ice. These deposits are called *eskers* (fig. 58). The contained sand and gravel is often well stratified and well sorted. Eskers are not too common due to the fact that they are often destroyed by ice movement or by post-glacial erosion.

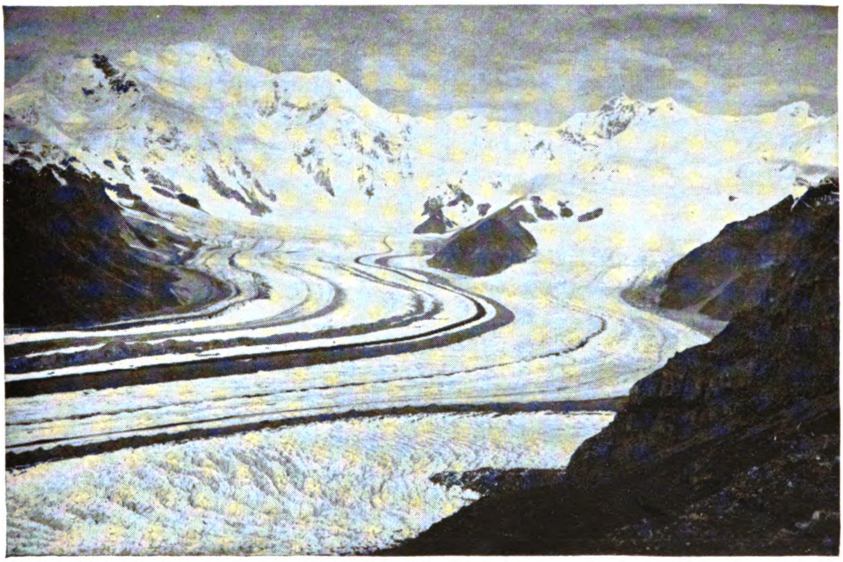

***Figure 56. Glacial moraines.***

(3) *Outwash plains.* Streams formed from melting ice which flowed away from the ice front commonly constructed broad, gently sloping *outwash plains* of sand and some gravel, locally well sorted (fig. 59). Many of these outwash plains are pitted with numerous undrained depressions, known as *kettles,* formed when huge blocks of glacier ice, covered with drift, melt, thus permitting the overlying drift to slump into


*Figure 57. A block diagram of a valley glacier showing the relationship and nature of the deposits.*

the space occupied by the ice. Outwash plains dotted with a complex of hills, ridges, and water-filled or swampy depressions (kettles) is referred to as *knob-and-kettle* topography (figs. 60 and 119).

(4) *Kame terraces.* In some continentally glaciated areas, step-like levels of sand and gravel deposits are found along valley

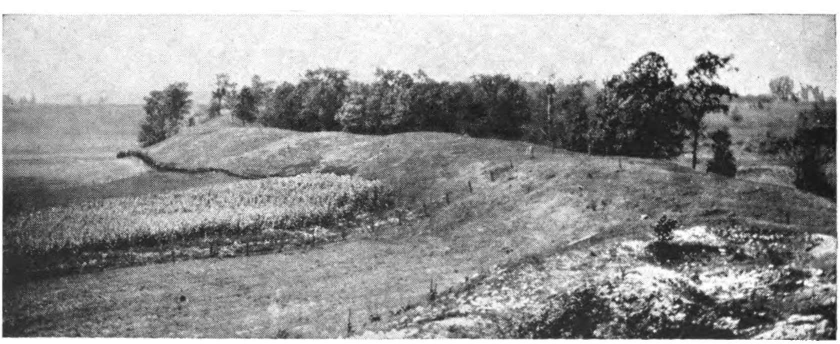

*Figure 58. Esker. Manitowoc County, Wisconsin.*

walls. These deposits carried in by meltwater from the glacier, are called *kame terraces.* They appear to represent locally developed streams and lakes formed between the side of the glacier and valley wall. They vary in size and normally are not very continuous deposits. The upper terraces may be less stratified than the lower, and frequently have pitted surfaces.

(5) *Glacial plains and plateaus.* After the continental ice sheets of Pleistocene time melted, enormous masses of debris which they had transported were left as a mantle of unconsolidated material with thicknesses as much as several hundred feet. Such a mantle of debris covers the underlying bedrock topography and produces a hummocky surface usually of low relief. The topography varies from fairly level land with scattered ridges and lakes to the complex knob-and-kettle topography. In many places the surface is strewn with large boulders called *erratics.* Associated with the till are some stratified sand and gravel deposits laid down by

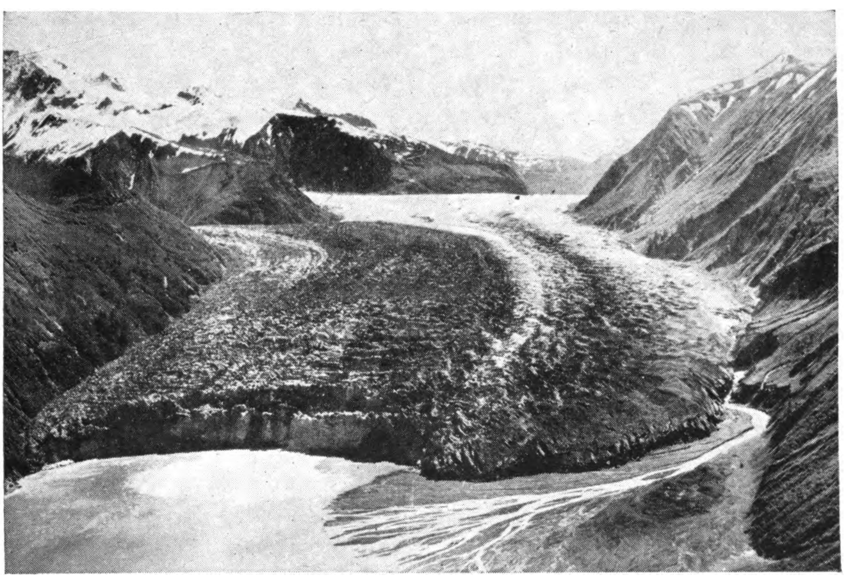

*Figure 59. Valley glacier on the Alaskan coast showing the development of kame terrace and outwash plain at right foreground. Crillon Glacier, Cituya Bay, Alaska.*

glacial streams. In some regions, low, smooth, oval or lenticular hills of glacial till, known as *drumlins* (fig. 61), may form vast "fields," that embellish the surface of the plain or plateau.

*Figure 60. Typical knob-and-kettle topography. Near Big Delta, Alaska.*

## 30. Wind

*a. Factors in Wind Erosion and Deposition.*

(1) *General.* Wind is an important agent of erosion in areas where loose, fine-grained surface materials are abundant and unprotected by a covering of vegetation. Such areas are deserts, stream bottoms in dry regions, and beaches.

(2) *Erosional processes.* Wind erosion is accomplished mainly by two methods: deflation and abrasion. The process by which air currents may pick up and move particles from the loose mantle is known as *deflation.* During this process, however, the particles being transported by the wind often strike against exposed bedrock or loose rock fragments. If the particles have sufficient hardness and the wind has sufficient velocity, the individual grains will, in time, chip off other small particles from the rocks which they encounter. This process which parallels stream abrasion is known as *wind abrasion.*

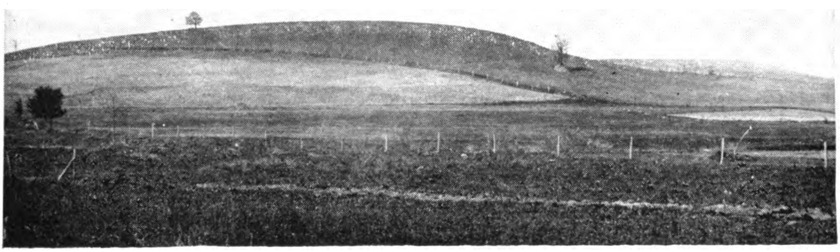

*Figure 61. Drumlin. Near Newark, New York.*

(3) *Deposition.* Except for the fact that deposition of sediment may be at elevations considerably higher than the source, atmospheric deposition does not vary appreciably from stream deposition. Material is dropped when the velocity of the wind is incapable of keeping the rock particles in suspension.

*b. Erosional Features.*

(1) *Ventifacts.* One special product of wind abrasion are polished and faceted pebbles known as *ventifacts.* In windswept areas, such as deserts, a rock or pebble may, in time, develop a facet on its windward side. Should the pebble become undermined and fall into a different position, a new facet may then be developed. The number and positions of these polished surfaces vary greatly.

(2) *Desert pavement.* In desert areas where the sediment contains an appreciable amount of large gravel or pebbles, *desert pavement* is sometimes produced. When the wind has carried away the smaller rock particles, the residue of larger pebbles settles and becomes tightly packed, protecting the fine material below. Subsequent wind abrasion across the top of this layer of pebbles tends to smooth and polish the upper surface. The different colors of the rocks sometimes give the pavement the appearance of a natural mosaic.

*c. Depositional Features.*

(1) *Dunes.*

(*a*) Wind-blown sand often accumulates in rounded or elongated hills or ridges called *dunes,* which form in much the same manner as snowdrifts. An obstruction, such as a boulder or a bush, causes a decrease in the wind velocity

with an accompanying deposition of sand on the lee side of the barrier. In time, the mound of sand is large enough to act as an obstruction to the wind and the dune grows larger in size. Deposition of sand occurs partly on the gentle front slope of the dune, but mainly on the steeper back slope.

(*b*) Dunes may take many shapes depending on the source and amount of sand and the characteristics of the wind. *Transverse dunes* commonly form on seacoasts or along the shores of big lakes where the supply of beach sand is abundant and the wind blows principally from one direction. These dunes form as long, sinuous ridges which extend in a direction perpendicular to the wind. As more sand is added, the dune tends to migrate inland in a direction away from the wind, while new ridges are formed to take its former place. Inland dunes formed in open country from a limited supply of sand are, commonly, crescent-shaped (barchanes) if the wind is moderately strong; or, are evenly spaced ridges extending in a direction parallel to the prevailing wind (longitudinal dunes) if the wind is strong.

(2) *Loess.* Material, called loess (par. 16*c*), consisting mostly of silt size particles and generally thought to be wind deposited, form broad tracts of land, plains, and plateaus in North America, western China, the Rhine valley, Russia, and South America. These deposits generally occur along the margins of glacial plains and major streams flowing from formerly glaciated regions. It blankets the underlying topography, tending to smooth out irregularities and produce gentle slopes. However, the peculiar ability of loess to stand in vertical walls produces very steep to precipitous escarpments along gullies, stream valleys, and artificial cuts (fig. 62).

## 31. Subsurface Water

*a. Factors in Subsurface-Water Erosion and Deposition.*

(1) *Erosion.* Although subsurface water is an important mechanical element in mass movement of the earth's mantle (pars. 23–25) its greatest erosional work is solution (par.

*Figure 62. Vertical face of loess in gully wall. Near Fort Adams, Mississippi.*

20*b* (5)) and transportation of the dissolved particles. This geologic work is most conspicuous in regions underlain by carbonate rocks, such as limestone, dolomite, and marble.

(2) *Deposition.* Mineral matter in solution is deposited by precipitation, the most important causes being evaporation, loss of carbon dioxide, changes in environmental conditions, activiites of plants and animals, and chemical reactions with solids and other fluids.

*b. Erosional Features.*

(1) *Caverns and sinkholes* (figs. 63 and 64). Depressions called sinkholes, formed by solution, are very distinctive surface features in many limestone regions. Water descending along vertical cracks and planes of stratification dissolve the limestone, forming *caverns* which increase in size until the overlying rock collapses and forms a *sinkhole.* Sinkholes may be dry or may contain small swamps or ponds if the openings to the subterranean channels are blocked. They are commonly widely spaced, ranging in size from a few feet to several miles in diameter and from a few feet to more than a hundred feet in depth. Where well developed, however, there may be as many as several hundred per square mile.

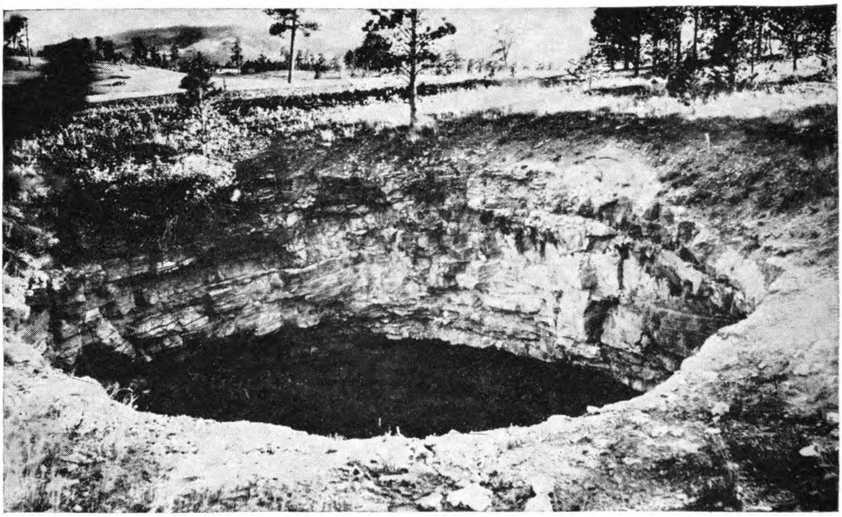

*Figure 63. Dry sinkhole with steep sides not modified by erosion. Near Cambria, Wyoming.*

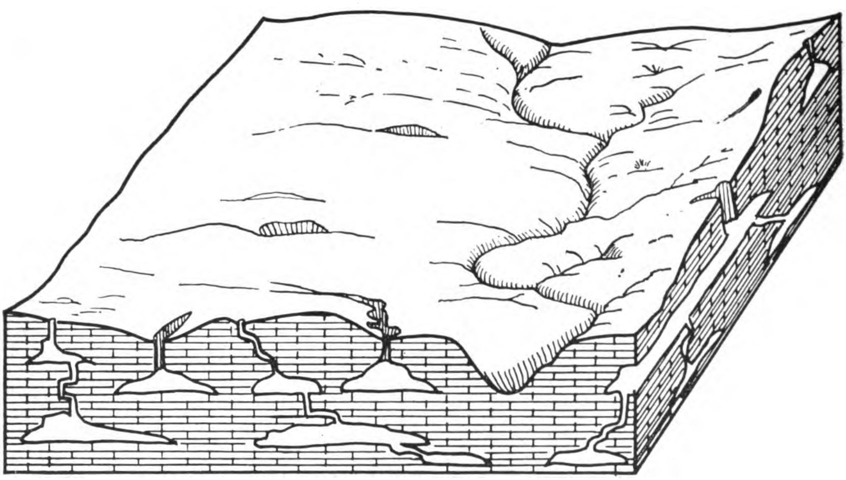

*Figure 64. Block diagram showing the development of caverns and sinks in limestone.*

(2) *Karst topography.* A distinctive type of erosional plain or plateau is developed on limestone. Limestone areas characterized by many sinkholes, valleys separated by steep-walled

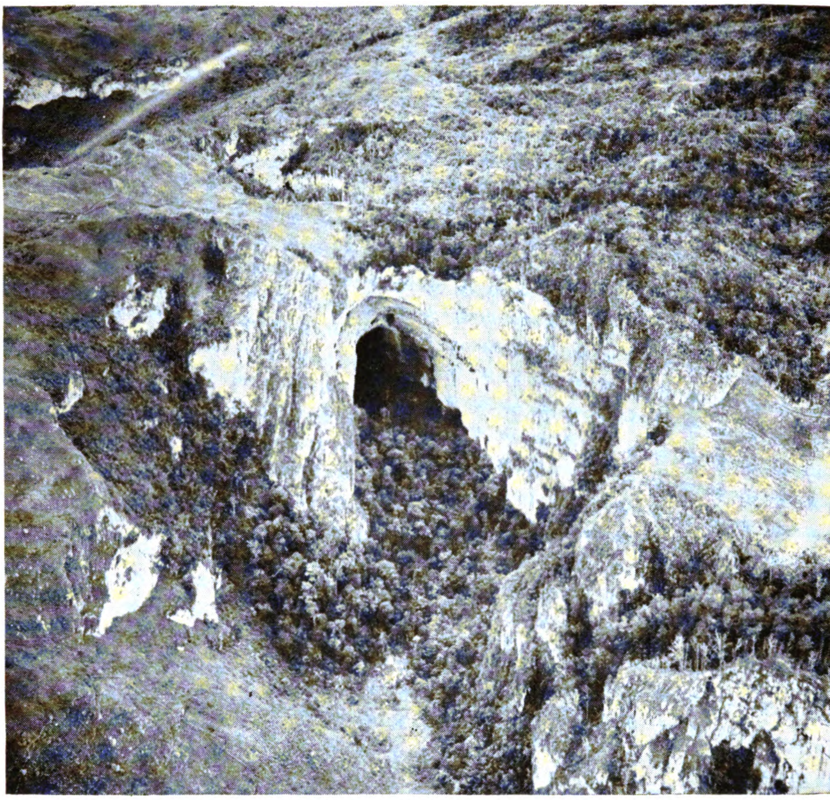

*Figure 65. Karst topography. Baliem, New Guinea.*

limestone ridges (fig. 65), disappearing streams, and little or no surface drainage are said to exhibit *karst topography*, named for the karst region of Italy and Yugoslavia where it is a striking feature. Karst topography is also well developed in the Ozarks of southern Missouri, in southern Indiana, and western Kentucky.

*c. Depositional Features.* The topographic features produced by deposition of mineral matter from subsurface water cannot be compared with forms produced by the other agencies of erosion. Most deposits are of so little importance to the military engineer, that a discussion of them is not warranted.

## Section V. PRINCIPLES OF SUBSURFACE WATER OCCURRENCE

### 32. General

The military engineer is concerned with subsurface water when he faces problems of water supply (pars. 148–187), land drainage, excavations and foundations (pars. 86–101), and control of mass movements of the earth (pars. 23–25). This section presents the principles of occurrence and movement of subsurface water that have an engineering significance. The erosional and depositional features of subsurface water are described in paragraph 31.

### 33. The Hydrologic Cycle

*a.* An understanding of the occurrence of subsurface water is based on general knowledge of the hydrologic cycle. The *hydrologic cycle* consists of the following processes: evaporation of water from oceans;

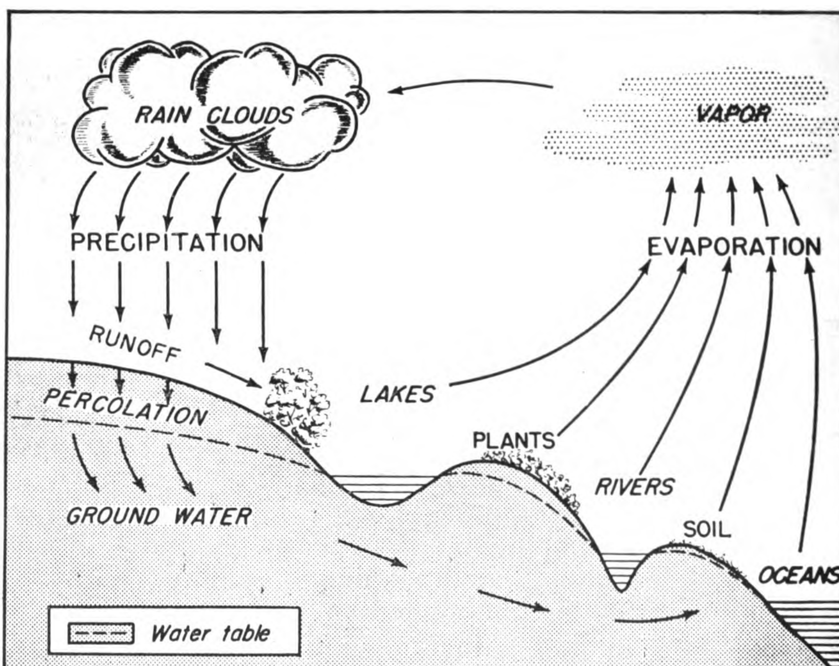


*Figure 66. The hydrologic cycle.*

condensation to produce cloud formations; precipitation of rain, snow, sleet, or hail upon land surface; dissipation of the rain or melted solids by direct runoff into lakes and streams, by seepage or infiltration into the soil and thence into underlying rock formations, and by direct evaporation; movement of water through the openings in the rocks; and issue of water at the surface through springs, streams, and lakes.

*b.* The cycle usually does not progress through a regular sequence, however, and may be interrupted or bypassed at any point. For example, rain which falls upon a heavily forested area soon may return to the atmosphere by direct evaporation or through transpiration by plants. Jungle-covered islands of the Southwest Pacific are known to produce more evaporation than do adjacent areas of ocean.

## 34. Classification of Subsurface Water

*a.* Water beneath the surface of the earth occurs in three zones: the *zone of soil moisture* where water temporarily is held in pore spaces by capillarity or other soil conditions; the *zone of aeration* or *zone of percolation* beneath the soil layer, where both water and air are present in the pore spaces; and the *zone of saturation* where all spaces are filled with water (① of fig. 67).

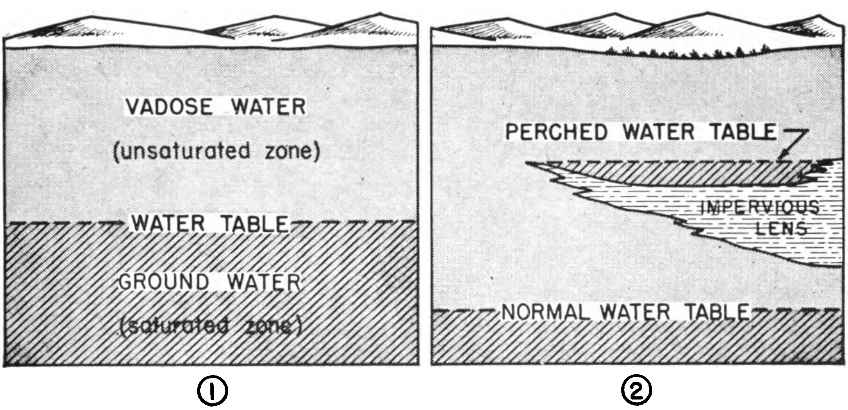


*Figure 67. Subsurface water zones.*

*b.* The zone of soil moisture and zone of aeration, usually grouped together as the *unsaturated zone,* contain what is commonly referred to as *vadose water* (① of fig. 67). The water in the zone of saturation is *ground water.*

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## 35. Water Table

*a.* The top of the zone of saturation is called the *water table* (① of fig. 67). It presents, in general, a subdued reflection of the surface topography. Its depth beneath the surface varies, depending on the surface topography, structure, rainfall, and the pore space in the soil or rock. If an impervious bed occurs between the land surface and the general water table of the area, a zone of saturation may exist above the water table, forming a localized *perched water table* (② of fig. 67).

*b.* If the water table intersects the land surface, as it may in the sides of valleys, water flows or seeps out as gravity springs or seeps (par. 40). Lake, swamp, and river levels are normally at the water table. If the water table sinks below a lake floor during a drought, the lake may become temporarily dry (fig. 68). In some wells, water stands approximately at the level of the water table; in others, water rises to the level of a hydrostatic head established by remote conditions, and the well has artesian flow (par. 39).

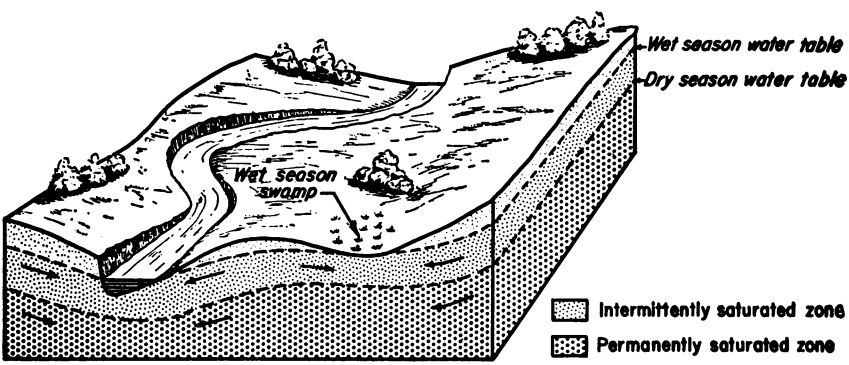


*Figure 68. Block diagram showing the relation of subsurface water to topography.*

## 36. Capillary Fringe

The zone of increased moisture which is invaribly encountered just above the water table is called the *capillary fringe*. It may be 5 to 10 feet thick in clays and shales, but is thin in coarse sands and gravels.

## 37. Aquifer

An aquifer is a soil or rock formation which will furnish enough water for a specific practical purpose. It has the same meaning as "water-bearing formation" or "water-bearing stratum." It is a relative term because a good aquifer for farm wells may be inadequate for a municipal supply or for a battalion or regiment.

## 38. Storage and Circulation

*a. General.* Ground water is not static. It moves slowly through pores or other openings in the soil or rock toward points of discharge and is replenished intermittently by rainfall in intake areas. Climate governs the amount of water contributed to the ground; porosity of the material governs the amount the ground will absorb. The rate of movement is controlled by gravity or hydrostatic pressure and by permeability.

*b. Porosity* (fig. 69).

(1) The porosity of a soil or rock is its amount of pore space. Expressed quantitatively, *porosity* is the percentage of the

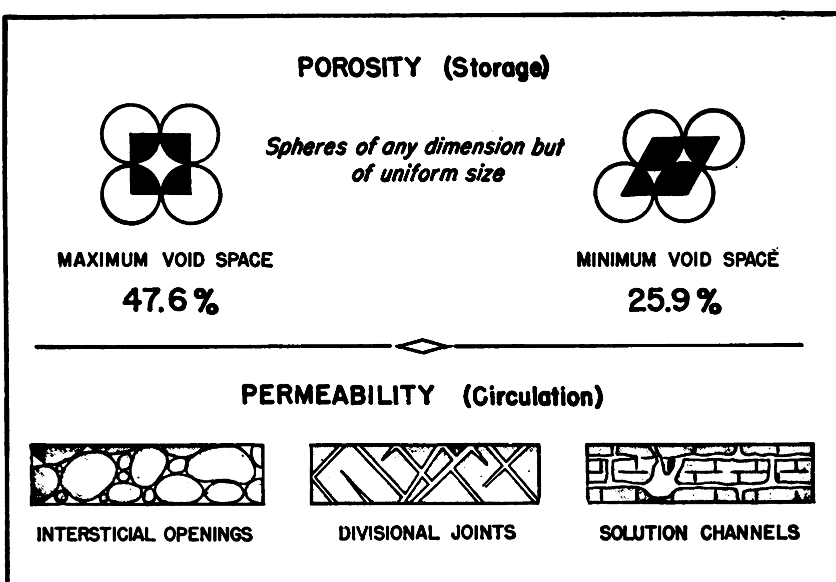


*Figure 69. Porosity and permeability.*

total volume of the material occupied by voids. The effective porosity (specific yield) is that part of the volume in the voids that will drain under gravity.

(2) The many types of soils and rocks differ greatly in the size, number, and arrangement of their pore spaces and, consequently, in their ability to contain and yield water. Those which are porous and capable of transmitting fluids are principally of clastic origin. Deposits of well sorted, uncemented sand and gravel are highly porous, regardless of grain size. Poorly sorted material has a relatively low porosity because smaller grains occupy spaces between the larger ones. The porosity in cemented and consolidated materials may be practically nonexistent.

(3) Porosity values of the different kinds of soil and rock (see also par. 15*b*) vary widely. The following percentage ranges are the most generally accepted:

| | *Percent voids* |
|---|---|
| Gravel and sand | 25 to 40 |
| Silt | 30 to 50 |
| Clay | 40 to 70 |
| Limestone | 5 to 30 |
| Sandstone | 5 to 25 |
| Shale | 5 |
| Igneous rocks generally less than 1 | |

(4) Fissures and caverns increase the water-holding capacity of rock. This in a sense is a factor in the porosity of a rock mass as a whole, but must be considered independent of the porosity of the rock variety itself.

*c. Permeability.*

(1) The permeability of a soil or rock is its capacity to transmit water under the influence of gravity or hydrostatic pressure. Materials through which water can pass freely are pervious or permeable; materials which will not transmit water freely are impervious or impermeable.

(2) The permeability of a soil or rock is not necessarily dependent on the porosity of the soil or rock. For example, clay has a high porosity value but is impervious because it has no continuous passageways wide enough to permit the flow of water, except by capillary action. Conversely, compact granite with essentially no pore spaces, may nevertheless be

permeable because of interconnecting joints and fissures through which water can flow freely. In general, however, to be readily permeable, a rock or soil must have porosity.

*d. Voids and Openings in Rocks.* The voids through which water may circulate can be either a part of the original structure of the rock or of secondary origin.

(1) *Primary structures.* Unconsolidated and partly consolidated clastic sedimentary rocks have interstitial openings between adjacent grains produced when the rock was formed (fig. 69). Extrusive igneous rocks have bubble holes or vesicles produced by escaping gases, and cavities produced by cooling and movement in lava flows. The gas cavities and caverns in lava flows, when the voids are interconnecting, have large aggregate volume in some areas and are important sources of water for springs and wells (fig. 201).

(2) *Secondary structures.* Secondary voids consist of cracks (fractures, fissures, joints, and faults), solution cavities, and the like (fig. 69). The permeability of igneous, metamorphic, and some of the more consolidated sedimentary rocks can be attributed to fractures in the rock mass. If the fractures are numerous and somewhat open, they are good channels for water movement and may yield large quantities of water.

## 39. General Artesian Conditions

*a.* Fundamentally, an artesian condition is one in which the water in a rock or soil layer is confined under hydrostatic pressure. A well exhibits artesian conditions when the water rises to some height above the aquifer from which it issues; the hydrostatic head may or may not be sufficient to force the water to the surface of the ground and produce a flowing well. In some localities the pressure, when originally tapped, has been sufficient to force water 100 to 200 feet into the air above the surface of the ground.

*b.* The basic conditions for artesian flow are a permeable aquifer to contain and conduct the water; relatively impervious formations above and below the aquifer to confine the water; an intake area where water enters the permeable bed; and a structure or dip which produces hydrostatic pressure upon water in the lower areas of the water-bearing formation. These conditions are illustrated in figure 70. If the intake area is high enough above the point of outflow, the

well will flow. The amount of hydraulic pressure or head always is subject to friction losses as the water moves through the aquifer.

## 40. Springs and Seeps

Subsurface water issues naturally at the earth's surface as springs or seeps. In *springs* the emerging water has a distinct current and is quite localized; in *seeps* the emergence is spread over a larger area.

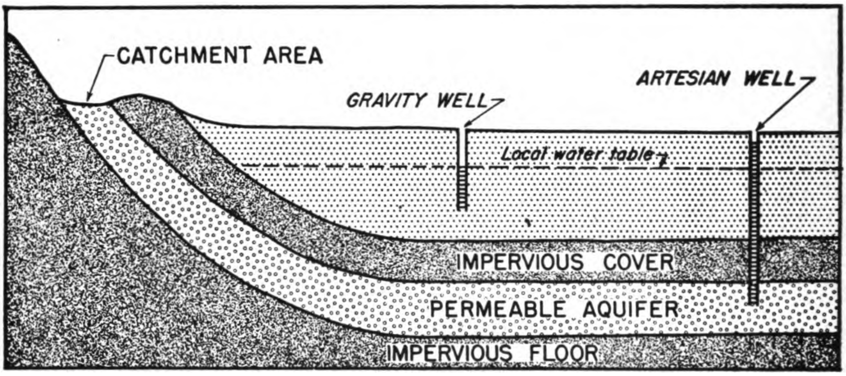


*Figure 70. Artesian conditions.*

Both originate under so many different conditions and in so many kinds of material that no single, simple classification is possible. For the purposes of this manual, two principal types of springs and seeps are recognized, gravity and artesian, based on the pressure of the emergent water and the structural conditions which make its emergence possible.

*a. Gravity Springs and Seeps.* Gravity springs and seeps may be described as those in which the subsurface water flows by gravity from a higher point of intake to a lower point of issue. The two important types are:

(1) *Water-table springs and seeps.* This type occurs where the water table comes near or intersects the surface of the ground, normally around the margins of depressions, along the slopes of valleys (① of fig. 71), and at the foot of alluvial fans (② of fig. 71).

(2) *Contact springs and seeps.* This type may occur along an exposed contact between an overlying pervious stratum and an underlying impervious stratum (③ of fig. 71). Contact

springs may appear at almost any elevation along a slope depending on the position of the contact.

*b. Artesian Springs.* Artesian springs occur where confined subsurface water, acting under the influence of a hydrostatic head, gains access to the surface of the ground. Fissures in the rock, fault zones (① of fig. 72), and, in some cases, solution channels may serve as avenues along which water can move to the surface. Artesian springs may also appear where a confined pervious stratum, containing water under pressure, outcrops at the surface (② of fig. 72).

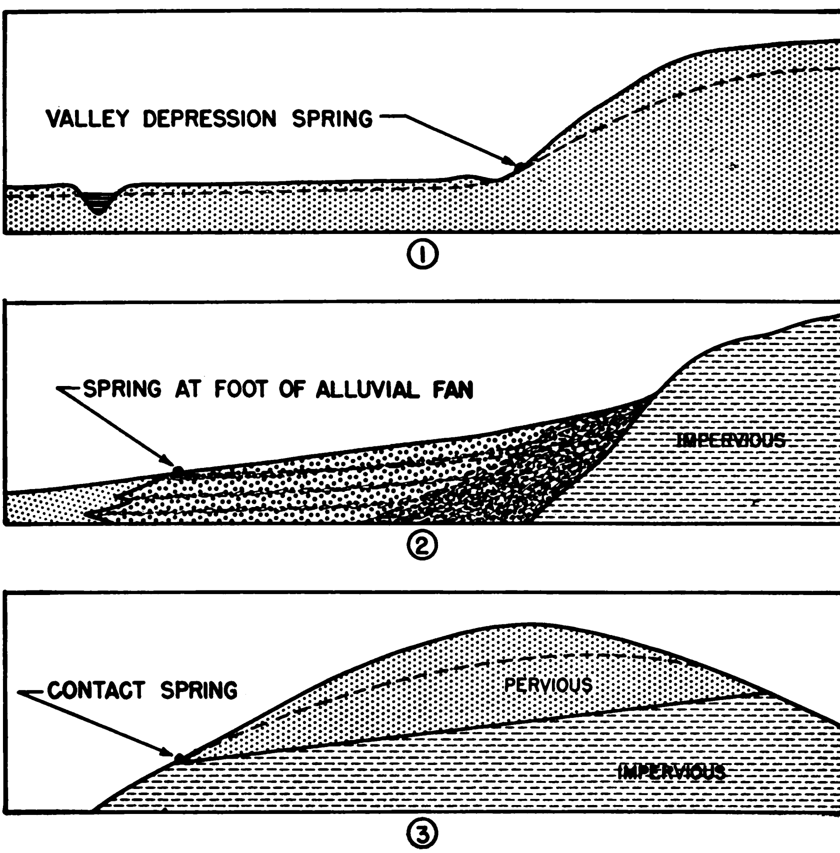


*Figure 71. Gravity springs.*

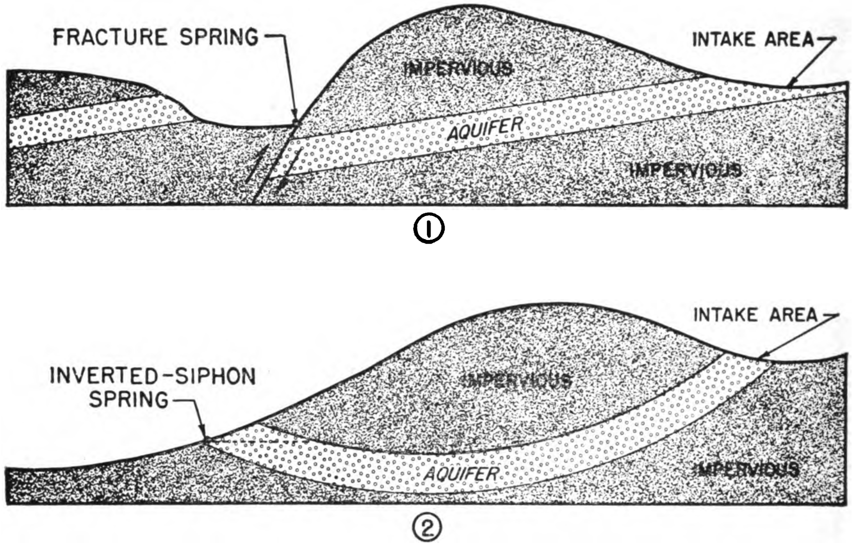


*Figure 72. Artesian springs.*

## Section VI. VOLCANOES AND VOLCANISM

### 41. General

*a.* The destructive action of the agencies of erosion which tend to level land masses are continuously opposed by two other processes which renew the irregularities of the earth's crust. One of these is *volcanism,* the movement and disposition of molten rock both under and on the earth's surface. The other process is earth movements (pars. 44–48).

*b.* This section discusses the topographic features produced by molten rock (lava) which has been extruded on the earth's surface or ejected from volcanoes. Intrusive rock structures produced by magmatic bodies which have solidified in the earth's interior are discussed in paragraph 12*b.*

### 42. Volcanoes

*a. Origin.*

(1) When magma rises toward the earth's surface, it commonly ascends through pipelike conduits or through fissures in the crust. Depending on the chemical composition of the magma

and the amount of contained gas, part or all of the molten rock that reaches the surface of the earth may issue forth as lava; part or all may be ejected (erupted) into the atmosphere where it cools rapidly, forming pyroclastic material (par. 12*b* (2)(*b*)). Slowly, by many eruptions, a cone-shaped hill or mountain called a *volcano* may be built up of successive lava flows or pyroclastic debris or combinations of both.

(2) Most volcanoes have eruptions separated by irregular intervals of inactivity. In a volcano's early stages, eruptions may be violent and almost continuous. As time goes on, eruptions usually become milder and more widely spaced, and ultimately cease. The life of a volcano may be a few weeks or months or it may be hundreds or thousands of years.

(3) Craterlike basins of volcanic origin developed by explosion or collapse during eruption are called *calderas* (figs. 73 and 75). Many calderas occur throughout the world; the most famous in the United States is Crater Lake in Oregon. Crater Lake is 5 to 6 miles in diameter.

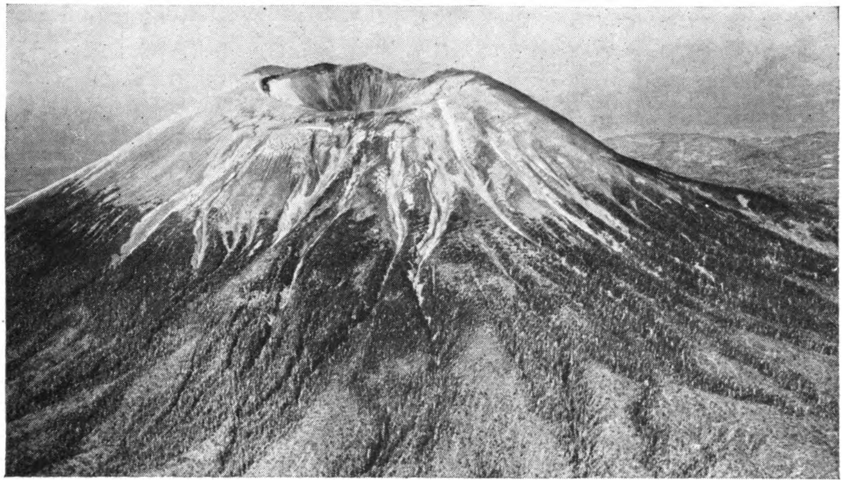

*Figure 73. Air view of volcano showing small crater (caldera) at apex of volcanic conduit.*

*b. Types.* Volcanic cones can be grouped into three basic types: cinder, lava, and composite, depending largely on the nature of the

molten material supplied to the volcano and on the nature of the eruptions.

(1) *Cinder cones* are steep-sided, nearly symmetrical volcanoes composed of pyroclastic material (fig. 74). Many examples of this type can be found in southwestern United States.

(2) *Lava cones* are composed of many layers of solidified lava that has been extruded without violent eruptions. Such

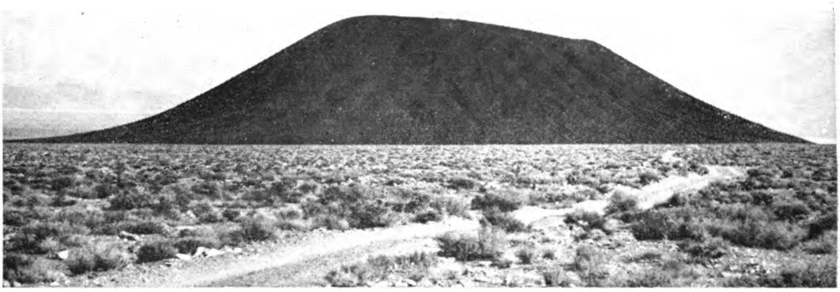

*Figure 74. Cinder cone. Clayton County, California.*

*Figure 75. Shield volcano. Mauna Loa, Hawaii.*

cones, usually referred to as *shield volcanoes* (fig. 75) are nearly flat and broad. The best examples of this type can be found on the island of Hawaii.

(3) *Composite cones* are those which have been built up with successive layers of pyroclastic material and lava and, for this reason, are commonly referred to as *stratovolcanoes.* This is a very common type of cone, and is easy to recognize by its concave, upward slope (fig. 76).


*Figure 76. Hypothetical section of a stratovolcano.*

c. *Damage From Volcanic Eruptions.*

(1) Eruptions in which the output of volcanic material is principally lava may destroy everything in its path, but the lava moves so slowly that it causes little loss of life.

(2) Eruptions in which the output of volcanic material consists of both hot gas and lava that is violently ejected into the amosphere may cause considerable damage and loss of life, particularly if the fall of pyroclastic material is in large quantities. During the eruption of Mt. Vesuvius in March 1944 (fig. 77), 84 B–25 airplanes were partially destroyed in a few minutes by pyroclastic material. The airplanes were located on the Pompeii airfield on the south slope of the volcano about 8 miles from the center of the crater. Some of the volcanic fragments had diameters as great as 5 to 8 inches and fell through the wings and fuselages of the aircraft. The surface accumulation of pyroclastic debris was 10 to 20 inches deep, making it necessary to abandon the airfield.

d. *Geographic Distribution.*

(1) Active volcanoes are especially numerous in a belt around the Pacific Ocean (fig. 78). Other regions of active volcanoes are the Mediterranean, Iceland, East Africa, and

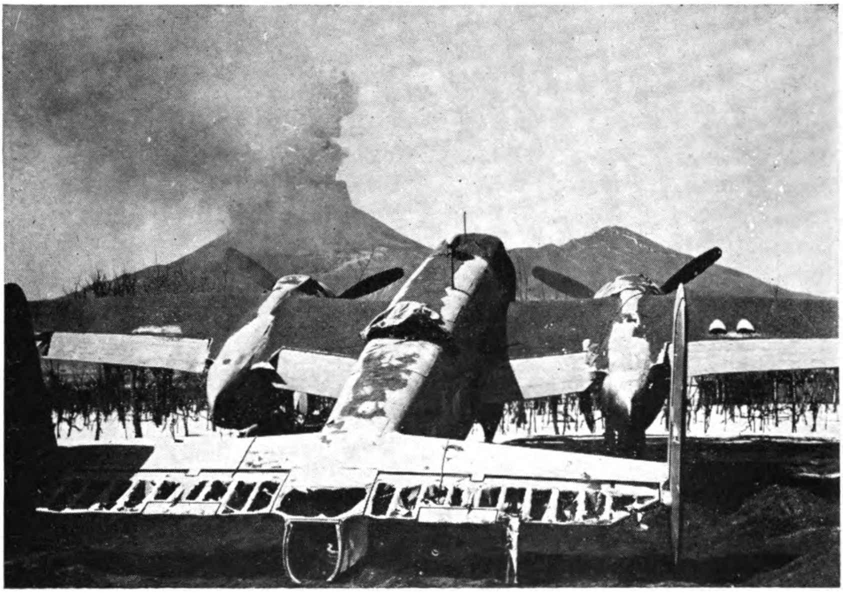

*Figure 77. Damaged B–25 on Pompeii airfield after eruption of Mt. Vesuvius.*

Hawaii. The occurrence of ancient volcanic rocks in many other parts of the world shows that, in the remote past, volcanoes did not have the same distribution as they have at present.

(2) In the United States, volcanic mountains are best developed in the Cascades Range of Washington, Oregon, and northern California. A series of volcanic peaks (Mount Ranier, Mount Adams, Mount Hood, Mount Shasta (fig. 79), and others), linearly disposed, surmount a dissected plateaulike upland, formed in part by lava flows. The latest eruption in this region was that of Lassen Peak, California, in 1914 and 1915.

## 43. Fissure Flows

*a.* Lava discharged through fissures in the earth's crust have produced, in some areas, immense plains or plateaus underlain by superposed, horizontal sheets of congealed lava. The eruption has been accomplished with little explosive activity (basaltic lava being the most common type extruded), and from fissures not connected with vol-

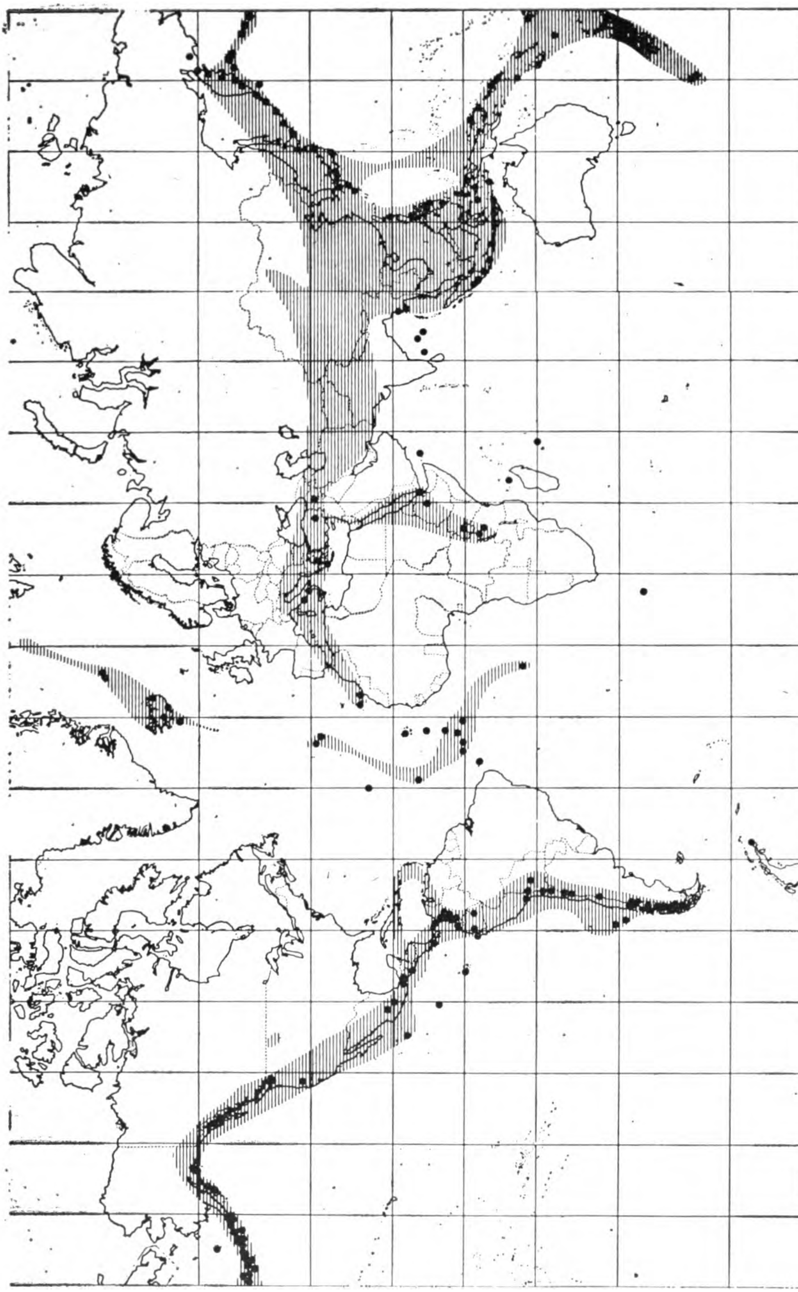

***Figure 78. Map of the world showing the location of active and recently extinct volcanoes (dots and belts shaded) where severe earthquakes occur.***

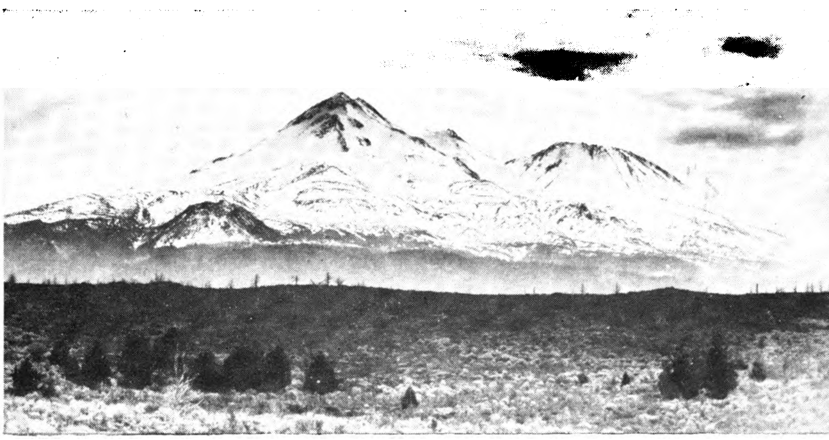

*Figure 79. Volcanic mountains, Cascade range.*

canoes. The surfaces of such areas are usually rough and irregular due to the unequal and uneven deposition of the individual lava sheets.

*b.* A basaltic plateau in the United States formed from fissure flows is the Columbia River plateau of Washington, Oregon, and Idaho (figs. 124 and 125). The lava sheets cover approximately 200,000 square miles and the succession of flows have a known, cumulative thickness of 4,000 feet. The Deccan plateaus (basalt) of central and western India (fig. 125), originally more extensive than the Columbia River Plateau, have lava sheets piled up to a thickness of 10,000 feet.

## Section VII. STRUCTURAL FEATURES AND MOVEMENTS OF THE EARTH'S CRUST

### 44. General

*a.* The land surface is neither fixed nor rigid. There is abundant evidence that some areas have been depressed, others have been elevated, and still others have been moved in a direction parallel to the circumference of the earth. Earthquakes are direct evidence of this movement. Beyond human history, indirect evidence has been recorded in the rocks. In particular, sedimentary rocks, by means of their stratification, exhibit structural and deformational features in a much more spectacular manner than do the other rock types. The record in the rocks indicates that deformation has ranged from broad

warps (continental movements) to severly folded, faulted, and jointed belts now occupied by mountains (mountain-building movements).

*b.* This section describes the secondary structural features such as folds, faults, and joints that have been formed by deformational processes operating within the earth's crust (par. 45). It also describes certain physiographic features of military importance (plains, plateaus, marine terraces, and mountains) whose inception can be attributed wholly or in part to earth movements (pars. 47 and 48). Earthquakes, a byproduct of earth movements, are discussed in paragraph 46.

## 45. Structural Features

Based upon the premise that sedimentary rocks were originally deposited in horizontal or nearly horizontal beds, the fact that they are frequently found tilted at all angles with the earth's surface is evidence that the attitude of the beds has been altered by earth movements. The structural features produced are folds, faults, and joints.

*a. Folds.*

(1) In regions characterized by crustal instability, the stratified

*Figure 80. Small anticlinal fold. Bank of Potomac River, Washington County, Maryland.*

rocks commonly yield to forces of earth movement by bending and crumpling. This folding is occasionally on a scale small enough to be observed in a single exposure (fig. 80), but more often it may only be inferred from ridges of relatively durable rock that are tilted at different angles in nearby outcrops (figs. 81 and 82). The position and inclination these strata occupy in the ground, referred to as the *attitude* of the beds, are accurately defined by two coordinates called strike and dip (fig. 83). The term *dip* designates the maximum angular departure of an inclined bed from the horizontal; the *strike* is the direction of the line formed by intersection of the bedding plane of the rock strata with a horizontal plane. Dip, expressed in degrees computed with a clinometer, is always measured at right angles to the line of strike. The strike direction, determined by means of a compass, is always given with reference to north.

*Figure 81. Limb of an anticline.*

*Figure 82. Aerial photograph of inclined beds. Rawlins, Wyoming.*

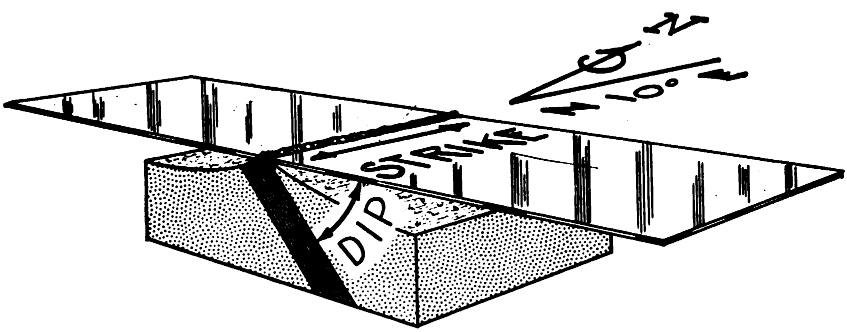


*Figure 83. Strike and dip.*

(2) In a series of folds, the up-arched parts are called *anticlines* (fig. 80), the trough-like parts are called *synclines* (fig. 84). An up-arched structure in which the beds dip away from a central point at its apex is called a *dome* (fig. 85). A local steepening of stratum which is otherwise horizontal or gently dipping is referred to as a *monocline.*

(3) Monoclinal structures should not be confused with *regional* or *structural dip,* a characteristic of the Coastal Plains where

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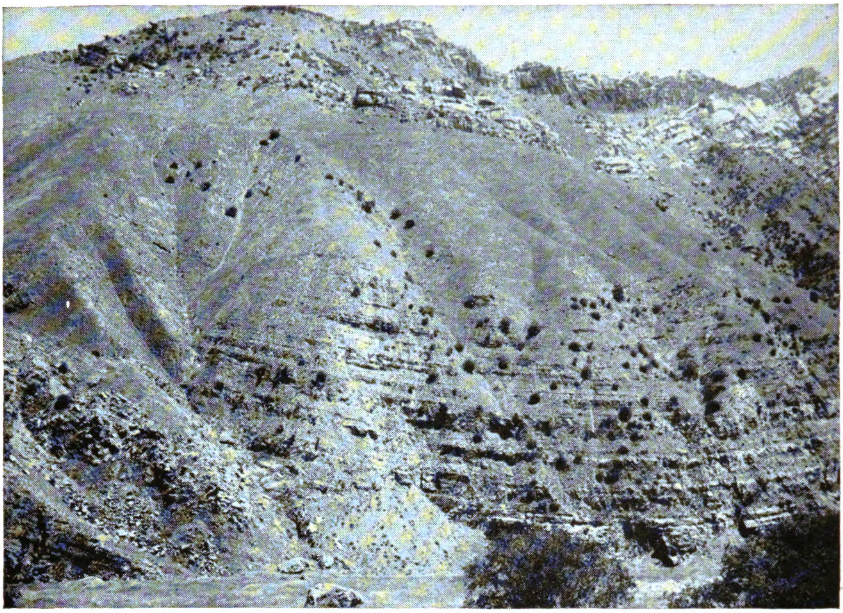

*Figure 84. Broad synclinal fold.*

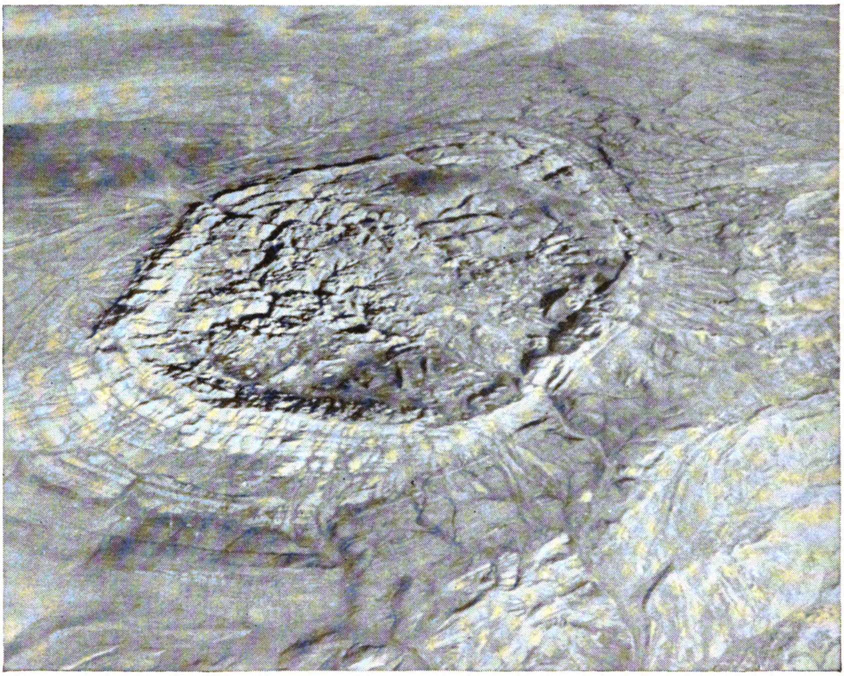

*Figure 85. Aerial photograph of an eroded dome. Canada.*

the rocks over a large area have a gentle dip in the same general direction. Where the underlying sediments dip more steeply than the ground surface, the truncated ends of the most resistant rock layers stand out in low ridges that more or less parallel the coast. The slope of these ridges is apt to be steeper on the landward side than on the seaward side. Such topographic features are called *cuestas.*

*b. Faults.*

(1) Any fractured surface along which there has been relative displacement of rock in any direction parallel to the fractured surface is called a *fault* (fig. 86). The magnitude of linear displacement may vary from inches to many feet or miles along the fault surface, and the lateral disturbance may be spread over a considerable area adjacent to the fault surface. This laterally fractured area, called the *fault zone,* usually contains pulverized rock or *gouge* and angular fragments of crushed rock or *breccia* that were produced during the movement of the fault blocks (fig. 87).

(2) Recognition of faults is of great importance to the engineer because faults represent zones of weakness in the earth's crust. In outcrops (fig. 86) they are easy to recognize as

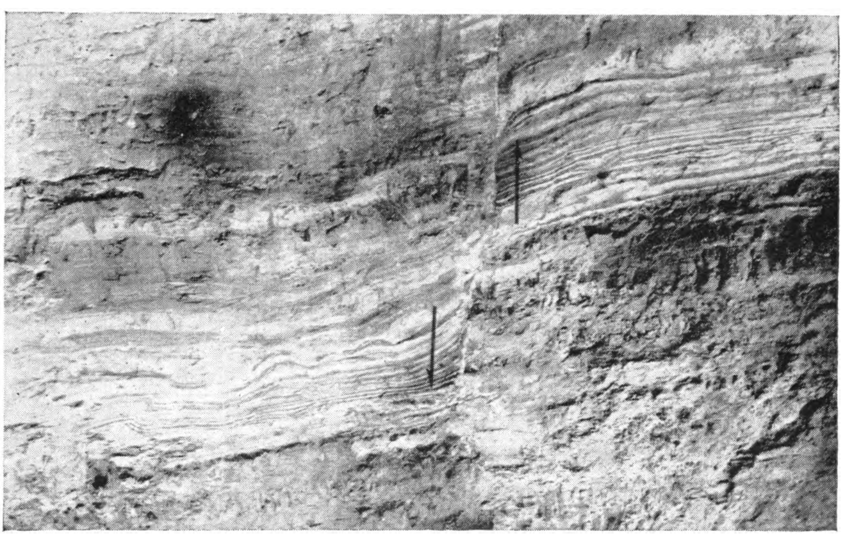

*Figure 86. Normal fault in sandy shale. Block on left has moved down relative to block on right.*

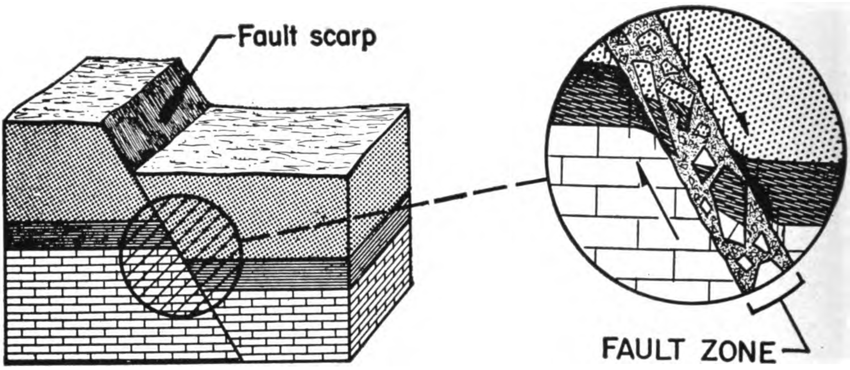


*Figure 87. Breccia and gouge contained in a fault zone.*

are many that appear in air photographs (fig. 88). Faults that are not visible, however, may often be discerned from differences in the geologic age, durability, or elevation of adjacent rock masses that can be detected by field observation or geologic mapping. For example, the contact between many long, straight mountain fronts in western United States terminates at a fault (fig. 89), along which movement has taken place in the past and, in some cases, along which movement intermittently occurs, producing earthquakes. A fault may also be represented by a long, straight valley eroded in the crushed and broken rock of the fault zone, or by a series of springs or seeps linearly distributed.

*c. Joints.* Fractures along which there has been little or no displacement parallel to the fractured surface are called *joints.* They cut across rock masses in different directions and various angles, forming a system of intersecting joints that divide the rock into blocks (fig. 90).

## 46. Localized Movements That Produce Earthquakes

*a. General.*

(1) *Major earthquakes* result from a sudden slipping of rocks along a large fracture or within a fracture zone. This movement jars the adjacent rocks, which transmit the shock in all directions as vibrations, the most intensive being near the center or *focus* or along the line of movement. The vibrations of a single shock commonly last for only a few seconds, but recurring activity along the same fracture may give rise

*Figure 88. San Andreas fault. California.*

to a succession of shocks, which may occure intermittently for several days. The original cause of the deep-seated movements that produce major earthquakes is still a matter of conjecture. It is known only that great rock masses slip suddenly on each other, sometimes for many feet, generally without warning.

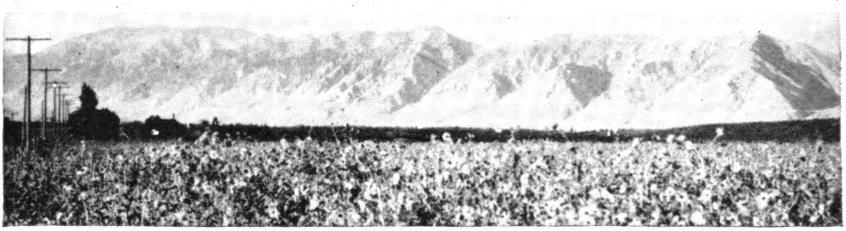

*Figure 89. Long, straight mountain front produced by faulting. California.*

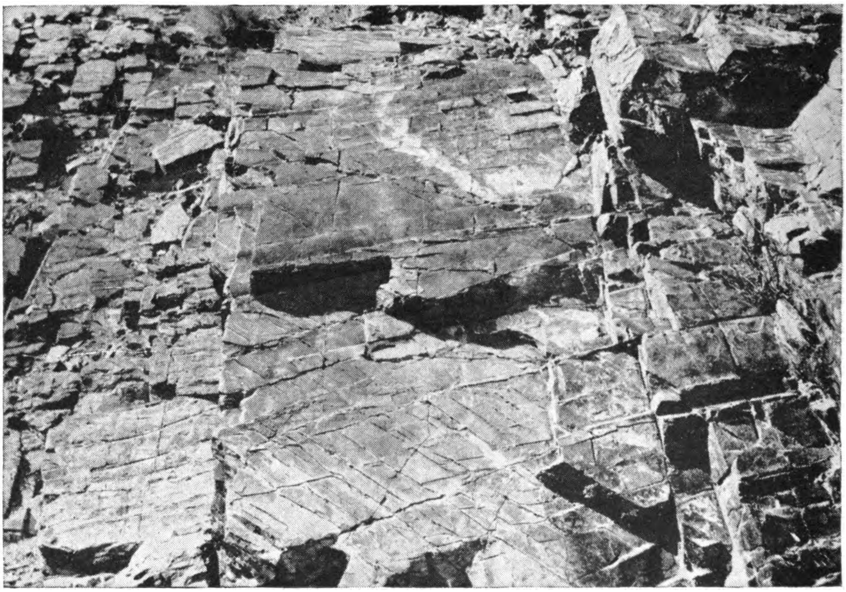

*Figure 90. Closely spaced joints in quartzite.*

(2) *Minor earthquakes* may be produced by landslides (par. 25*b*), volcanic eruptions (par. 42), or man-made explosions.

*b. Damage From Earthquakes* (fig. 91).

(1) Thousands of earthquakes are recorded each year by seismographs located in various parts of the world. Of these, only a very small percent actually cause any damage, and still a smaller fraction cause extensive damage. Damage by earth-

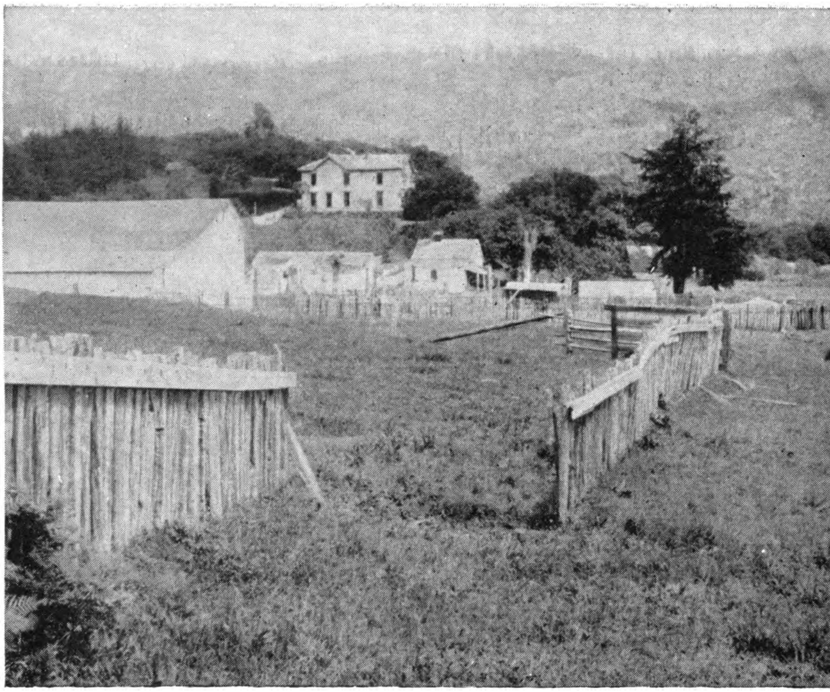

*Figure 91. Fence displaced due to earthquake.*

quakes can be minimized by proper location and construction of structures as discussed in paragraph 90*b*.

(2) In coastal cities, damage is sometimes caused by huge sea waves or *tsunamis* (incorrectly referred to as "tidal" waves) that sweep over the lowlands adjacent to the sea. Many of these waves result from volcanic eruptions and many from disturbances of an unknown origin in the ocean floor.

*c. Distribution of Earthquakes.* No part of the earth's surface is free from earthquake tremors, but the more violent or destructive shocks are much more frequent in some places than in others. The areas of most numerous severe shocks are shown in figure 78. They consist primarily of two belts, one almost encircling the Pacific Ocean and the other running across the Mediterranean and into central Asia. These belts closely parallel the belts of active volcanoes, and there are many examples of earthquakes immediately preceding or following nearby volcanic activity. Although this parallelism would seem to imply at least an indirect relation between the two phenomena, there

is often no apparent relation between any given earthquake and visible activity in the same locality.

## 47. Continental Movements That Produce Inland Plains, Plateaus, and Marine Terraces

Continental movements are defined as broad or regional uplifts that affect extremely large areas. Deformation is moderate and essentially in a vertical direction. The broad warps are formed on such a large scale that they must be studied in widely separated localities in order to be interpreted accurately. Although the movement is not rapid, the cumulative effect is often more pronounced than the movement that accompanies earthquakes. Common physiographic forms produced by these continental uplifts are plateaus, many of the inland plains, and the terraces which flank most of the continents and many islands.

*a. Plateaus.*

(1) In the main, a plateau exhibits a high relief and level surface. The precipitous rise of the land above the present level of the streams is the result of regional uplift. The level surface may represent a peneplane developed by erosional forces or a level surface produced by or developed upon horizontally deposited strata. The Laurentian Plateau in eastern Canada is an example of an erosional plateau; the Colorado Plateaus (fig. 109) contain many excellent examples of the depositional plateau.

(2) Plateau remnants in a highly dissected region are often referred to as "mountains of erosion."

*b. Marine Terraces.* The flat benches and prairie lands, which in places border the coast and lie at abnormal positions as much as several hundred feet above the water level, are produced by earth movements of more or less continental magnitude. These steplike features are referred to as marine terraces. Like plains and plateaus, marine terraces are either erosional or depositional, both types representing previous levels of the sea.

(1) *Erosional marine terraces* are for the most part wave-cut benches which are separated, generally, by precipitous wave-cut cliffs (fig. 92). They have a world-wide distribution. They are very common along the west coast of the United States and along many islands in the Pacific Ocean, coral

islands included (fig. 93). In the Pacific Ocean marine terraces are developed at levels up to 1,500 feet, although the most persistent levels are at 25 to 35 feet, 60 to 65 feet, and about 100 feet. Many represent levels of coral reef development or erosion of elevated coral reefs.

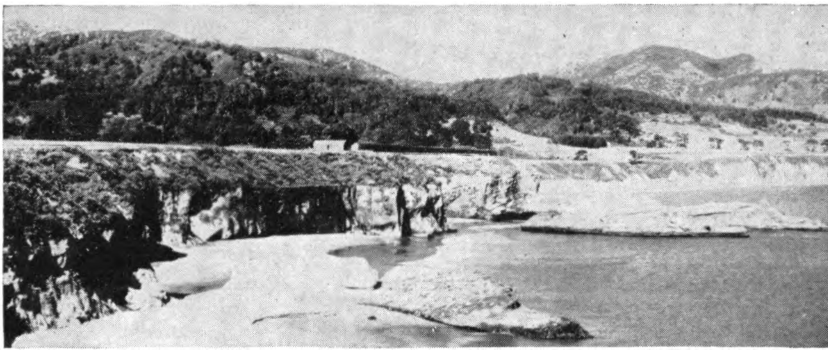

*Figure 92. Erosional terrace typical of many coastlines.*

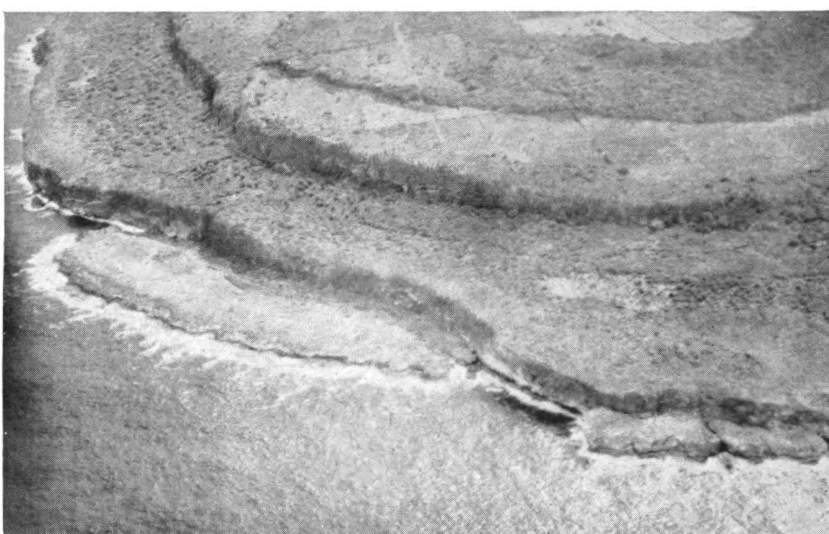

*Figure 93. Erosional terrace on a coral island. South West Pacific.*

(2) *Depositional marine terraces,* known as *coastwise terraces* in the coastal regions of Louisiana and Texas, consist of marine or deltaic sediments that have been raised above the present

sea level. The steepened slopes between the depositional terrace surfaces are commonly not as abrupt as the slopes between the terraces formed of wave-cut benches. These coastwise terraces merge with many of the terraces that parallel the river valleys.

## 48. Mountain-Building Movements

Mountain-building movements usually occur in relatively narrow belts in the earth's crust. Based upon the type of deformation (compressional or tensional) and the predominant structural feature produced, the following mountain types are recognized.

*a. Fold Mountains.* Mountains like the Appalachians in the eastern United States (fig. 97) and the Ouachitas in Oklahoma and Arkansas (b on fig. 110) are composed of beds or rocks which have been compressed into folds, suggestive of corrugated paper. There the beds lie at steep angles to the horizontal and are even vertical or

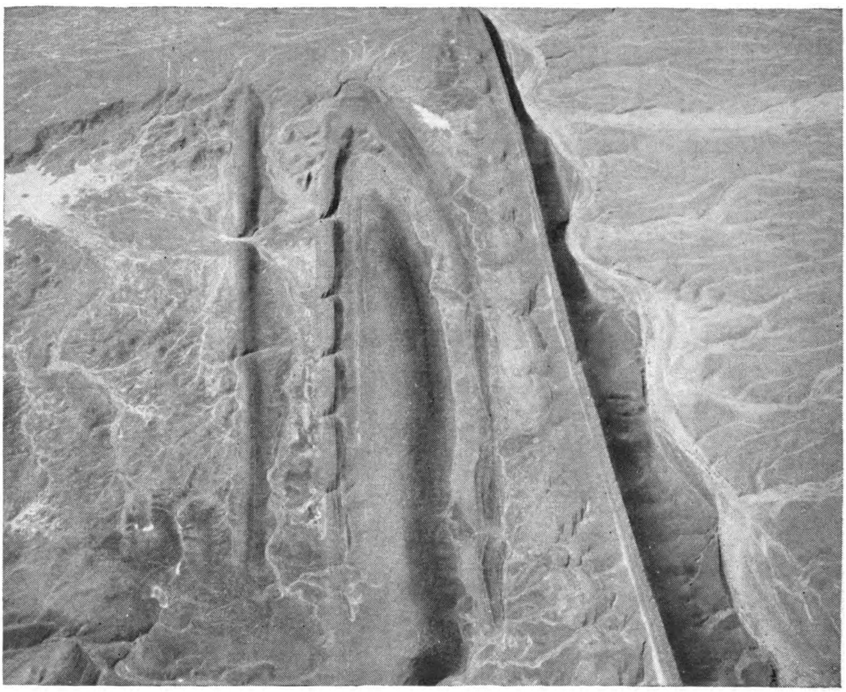

*Figure 94. Plunging fold. Africa.*

overturned in places. The selective erosion of beds which differ greatly in durability has produced distinctive valley and ridge topography. The relatively soft layers, like shale and some limestone, have been excavated into valleys, while the intervening layers of more resistant rock, like sandstone, quartzite, and conglomerate stand out to form ridges. A series of parallel ridges and valleys have resulted from the erosion of these folds and, in some places, arcuate ridges have resulted where the beds converge around the end of a dipping fold (plunging fold) as shown in figure 94. Ridges so formed are long and narrow and commonly unsymmetrical in cross section. The side with the most gentle slope represents the surface of an inclined resistant layer.

*b. Fault-Block Mountains.*

(1) Mountains such as those in the Basin and Range physiographic province of Nevada and adjacent states have resulted mainly from faulting (fig. 108). Numerous blocks bounded by faults have been raised or depressed relative to each other. The raised and tilted blocks form the ranges. The depressed blocks form valleys in which shallow lakes, known as *playa lakes* (fig. 95), may exist for a few days after rains, but become flat expanses the remainder of the time.

(2) Individual blocks may be geologically complex and composed of folded, faulted, and metamorphosed rocks of various compositions. Little-modified blocks are bounded by fault scarps or, if tilted, by a scarp on one side and a broad gentle back-

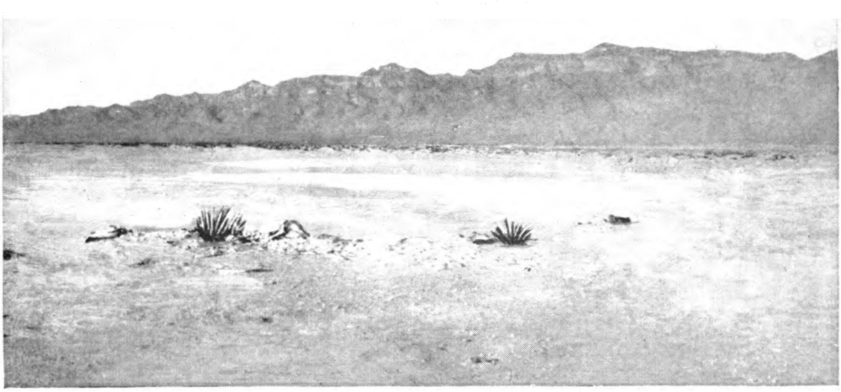

*Figure 95. Playa lake. White Valley, western Utah.*

slope on the other. As they erode they may become so modified that they give little outward evidence of being fault blocks. In the arid regions of the Southwest, the ranges commonly develop deeply ravined slopes and serrated crests.

*c. Dome Mountains.* Dome mountains consist of broad, more or less circular upfolds (figs. 85 and *f* on fig. 107). The domes may be composed of massive crystalline rocks. Commonly, the high central core of crystalline rock is encircled by outward-sloping sedimentary beds which originally covered the entire dome, having since been eroded from the central part. In places, however, the sedimentary cover remains above the domes as in the case of a part of the Laramie Range of Colorado. The eroded beds remain as long, low, sharp-crested ridges which border the mountains in concentric bands. Such ridges are called *hogbacks* (fig. 96). Frequently their steep slopes face toward the mountains while their broader, gentler slopes face away from the mountains.

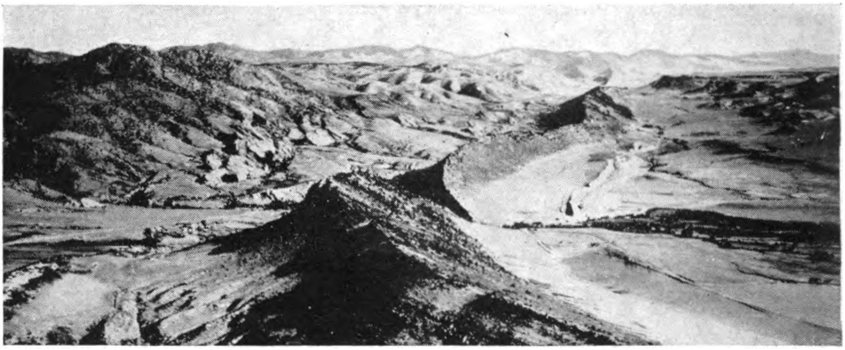

*Figure 96. Hogback ridges flanking the east of the Front Range. Rocky Mountains.*

*d. Complex Mountains.* Large ranges and mountain chains, such as the Northern Rocky Mountains (*d* on fig. 107) are complex in nature and contain a variety of the forms described in *a, b,* and *c* above, because different materials compose them and different processes have shaped their separate parts.

*e. Volcanic Mountains.* See paragraph 42*d*(2).

## Section VIII. GEOLOGIC HISTORY

### 49. Reconstruction of Geologic History

*a. Local Sequence of Events.* Reconstructing the geologic history of a region is much like putting together the pieces of a puzzle. In any small area some of the pieces fit together easily. If an outcrop shows folded sedimentary beds cut by a fault, for example, the following events must have taken place: submergence, deposition of sediment and consolidation into rock, folding and emergence of the beds, breaking of the beds along the fault, erosion of the beds to the present time. If the beds contain marine fossils, uplift of the land above the ocean floor must be another episode in the history. If one of the beds is made of volcanic ash, a period of volcanic activity is indicated.

*b. Correlation from Place to Place.*

(1) Difficulties begin when the sequence of events indicated at one outcrop is compared with that at another. If sandstone appears in one outcrop and shale in an outcrop half a mile away, how can we tell which was deposited first? Were they formed at the same time, one in shallow water and one in deep water? If the sandstone is cut by a fault and the shale by a basalt dike, how can we tell whether faulting occurred before, during, or after intrusion of the dike?

(2) An important aid in the correlation of beds from place to place is furnished by the study of fossils. Living forms have changed greatly in the course of geologic history, so that, in general, beds deposited at any one period will have fossils different from those formed at another period. Beds in different parts of the country or even in different parts of the world are assumed to belong to the same part of geologic history if their fossils are similar. Furthermore, once a sequence of fossil forms is established for a series of beds, beds in other places can be arranged in the order of their formation by the way their fossils fit into the established sequence.

*c. Dating Geologic Events.* Since fossils can be arranged in order of development from one rock layer to another, they can be used as a time-scale to date geologic events. Fossils of course can indicate only relative dates, not dates in years. To determine actual dates in years, the most reliable method appears to be a study of the rate of the disintegration of radioactive minerals in igneous rocks. This method

has been applied successfully to only a few rocks, but enough absolute dates can be used to bridge the gaps. Most of the measured dates are tens of millions or hundreds of millions of years; the oldest rocks of which we have knowledge go back nearly 2 billion years.

*d. Slowness of Geologic Change.* Geologic processes of the past have been much like those observable at present. Some of them at times are more active or less active than they are today, but not essentially different. Streams wash sediments from their valleys, waves eat into their shores, waters deposit silt over floodplains, volcanoes spread ash and lava over large areas. Ordinarily, these changes appear to be very minor. In a month or a year or even in a lifetime the alteration in most landscapes is almost imperceptible. If the processes at work today continue for millions of years, however, their cumulative effect will be very large, large enough to account for the wearing down of whole mountain ranges, for the elevation of marine sediments to high altitudes, and for the accumulation of lava flows thousands of feet thick. Such results are often assumed, with little or no evidence, to have been caused by violent cataclysms, such as the upheaval of a mountain range overnight, a universal deluge, or seas of molten rock poured out on the surface. The records we have of past geologic events seem to indicate that rocks and landscapes have been formed by slow processes acting through long ages.

## 50. Mountain Building

*a.* The major events in geologic history are episodes of mountain building. They are landmarks by which geologic history can be subdivided, much as human history is subdivided by wars and by social and economic revolutions. Episodes of mountain building are times when crustal movement and igneous activity are more intense than usual. This does not mean that mountains and volcanoes are formed overnight but that, during a few million years, large mountain ranges were formed in one or more parts of the earth.

*b.* Episodes of mountain building commonly follow long periods of erosion and sedimentation. During the quiescent periods, shallow seas (like the present Hudson Bay and Baltic Sea) spread widely over the continents. Marine sediments accumulate in the seas, and the sea floor gradually sinks as the deposits grow thicker (1 of fig. 97). Slowly the sediments harden into rock as more and more weight is added. Mountain building commences with the weakening and com-

pression of the sedimentary accumulation. Compression squeezes the beds into folds and, in places, forces them above sea level (② of fig. 97). Erosion begins as soon as the land emerges and continues all through the slow rise of the mountains. Compression becomes so intense that thrust faults as well as folds develop, one part of the folded mass riding up over another part. The disturbance sets molten rock in motion at the base of the mountain folds. Dikes, sills, and batholiths are intruded into the folded beds, and volcanoes appear at the surface. Some of the sedimentary rock is metamorphosed or altered by the heat and pressure that accompany the folding and the

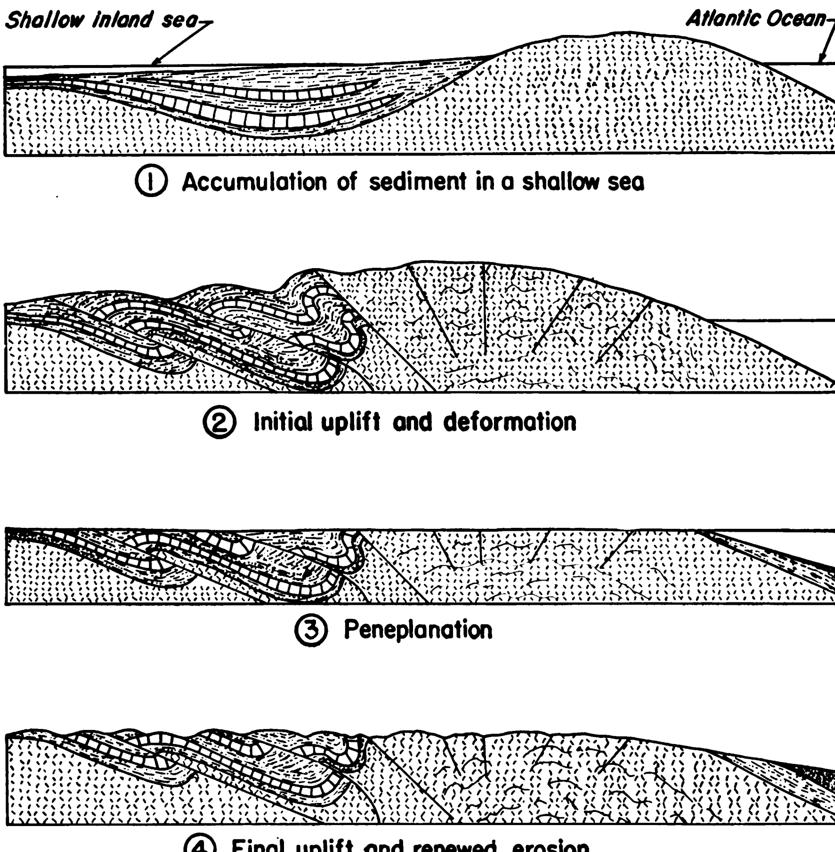


*Figure 97. Schemanc sections showing the principal stages in the history of the Appalachian Mountains.*

intrusion of igneous rocks. Gradually the activity dies down and erosion cuts more and more deeply into the mountains, ultimately exposing the hardened igneous rocks at the core of the range. In the following period of quiescence, the mountains are worn down to a nearly level surface (③ of fig. 97). Later uplift may renew erosion and produce a new mountain range on the stumps of the old, as in the case of the Appalachians (④ of fig. 97).

*c.* Not all mountains have been formed by this sequence of events. Some volcanoes, for instance, build huge cones in regions far from any active folding. Some ranges are formed by uplift and tilting of blocks along faults, like most of the mountains in Nevada and Utah. Some mountains come into existence by the action of erosion of plains gradually lifted high above sea level. A good example is the Catskill Mountains. The major mountain chains of the earth were built, at least in their original form, by the crumpling and uplift of thick sediments accumulated in subsiding basins.

## 51. Divisions of Geologic History

Geologic history and the rocks that record it are divided into eras, periods, epochs, and ages (table VI). The major divisions, eras, and periods, are divided by episodes of mountain building that alternate with long intervals of quiescence and deposition. The smaller subdivisions, epochs and ages, are differentiated on localized breaks in the sedimentary record.

*a. Eras.* Episodes of intense mountain building on a world-wide scale initiated the major geologic time divisions called *eras.*

(1) The *Cenozoic era* is the most recent and is still continuing. Its beginning was roughly the time when such mountains as the Rockies, Andes, and Alps began to rise for the first time.

(2) The *Mesozoic era* preceded the Cenozoic. It began roughly with the first appearance of mountains on the site of the present Appalachians, Urals, and others.

(3) The *Paleozoic era* is still older. Its beginning dates from the formation of mountains recognizable today only by their eroded stumps, as in many places of eastern and central North America.

(4) *The pre-Cambrian era* is a general term for all geologic time before the Paleozoic. Most probably it consists of two or three eras separated by times of widespread mountain build-

ing, but the geologic history is obscure. Most of the rocks are metamorphosed and fossils are absent or poorly preserved.

*b. Periods.*

(1) Less severe but world-wide episodes of mountain building subdivide the eras into *periods*. Table VI lists the generally accepted period names. With minor modifications these terms are used by geologists throughout the world.

*Table VI. Divisions of Geologic Time.*

| Eras | Periods | Rock symbol | Predominant life |
|---|---|---|---|
| Cenozoic (–60 million years ago). | Quaternary (Recent) (Pleistocene). | Q | Age of man. |
| | Tertiary | T | Age of mammals. |
| Mesozoic (60–200 million years ago). | Cretaceous | K | Age of giant reptiles. |
| | Jurassic | J | |
| | Triassic | Tr | |
| Paleozoic (200–500 million years ago). | Permian | P | Age of primitive reptiles. |
| | Carboniferous (Pennsylvanian) (Mississippian). | C | Extensive coal swamps. |
| | Devonian | D | Age of fishes. |
| | Silurian | S | Widespread ancient coral reefs. |
| | Ordovician | O | Primitive fishes. |
| | Cambrian | C | Primitive marine invertebrates. |
| Pre-Cambrian (500–2000 million years ago). | Divisions not standardized. | | |

(2) Periods are usually named after a locality where the rocks of such age are best and most typically developed. Periods, therefore, bear geographic names. The Permian period for example, is named after the town of Perm in the Ural Mountains, and the Devonian period after the county of Devon in England.

*c. Epochs and Ages.* Periods, in turn, are subdivided into smaller time units called *epochs* and *ages*. A great many epoch and age names are used throughout the world; many are of local significance only. Like periods, they are usually named after a locality where the rocks are best and most typically developed.

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# CHAPTER 3

# MAPS AND LITERATURE AS SOURCES OF GEOLOGIC INFORMATION

## Section I. GENERAL

### 52. Planning and Operations

Geologic information is often needed for the planning of military operations. It is valuable for the initial acquaintance with an area, and it may help confine reconnaissance to areas of greatest interest. To the engineer, advance geologic information may reduce the need for costly prospecting, excavations, and drilling, and help avoid construction failures on unfavorable ground.

### 53. Sources of Geologic Information

*a. Standard Sources.* The standard sources of geologic information most commonly available are given in paragraphs 54 and 55. These sources include geologic maps and literature which are wholly devoted to geology (primary sources of geologic information); and such items as soils maps and reports, topographic maps, and aerial photographs which can be interpreted geologically (secondary sources of geologic information). Both the primary and secondary sources however, have not been created directly for military use. All standard sources of geologic information must, therefore, be interpolated to make them useful for military planning and operations.

*b. Special Sources.* Special sources of geologic information are scientific publications and intelligence reports.

(1) Scientists have explored and reported on almost all parts of the world and their literature has been freely disseminated. This scientific literature, when standard sources of geologic information are not available, is a valuable source of information on terrain and engineering problems.

(2) Intelligence reports discussed in section III below, if available, provide ready-made geologic interpretations for a variety of military problems. Paragraphs 58–61 show how the standard sources of geologic information can be used in the preparation of intelligence reports that yield information of military value.

## Section II. STANDARD SOURCES OF GEOLOGIC INFORMATION

### 54. Geologic Maps as a Primary Source of Geologic Information

*a. Introduction.* The basic concern of the geologist is the interpretation of events in the history of the earth, and their sequence, as indicated by the rocks that are available to him as the ancient record of such events. For this reason, geologic maps identify rocks by their geologic age.

*b. Geologic Map Symbols.* Generally the smallest rock unit that is mapped is a *formation.* A formation is an individual bed or several beds of rock that extend over a fairly large area and that can be clearly differentiated from overlying or underlying beds because of a distinct difference in lithology, structure, or age. Geologic maps indicate the areal extent of these formations by means of letter symbols, color, and symbolic patterns.

(1) The letter symbols that identify map units commonly indicate the formation and the period. For example, in appendix II, Tr indicates rocks of the Sugarloaf formation of Triassic age. The standard letter symbols for the periods are shown on table VI.

(2) Standard color and pattern conventions are followed on maps produced by the U. S. Geological Survey. Tints of yellow and orange are used for different Cenozoic rocks, tints of green for Mesozoic rocks, tints of blue and purple for Paleozoic rocks, and tints of russet and red for pre-Cambrian rocks.

(3) Patterns used depict, as far as practicable, the primary structural features of the rock types. Variations of dot and line patterns are used for sedimentary rocks, wavy lines for metamorphic rocks, and checks, crosses, or crystallike patterns for igneous rocks. Foreign maps may use similar or different conventions.

(4) Another type of symbol common on geologic maps indicates the attitude of structural features of the rock strata. The *structural symbols* shown on figure 98 are among those that are most commonly used. The long line of a dip-strike symbol indicates direction of strike of a rock bed, fault, fold, or flow structure; the short line indicates the direction of dip. The small figure at the side of a dip symbol indicates the angle of dip from the horizontal, in degrees.

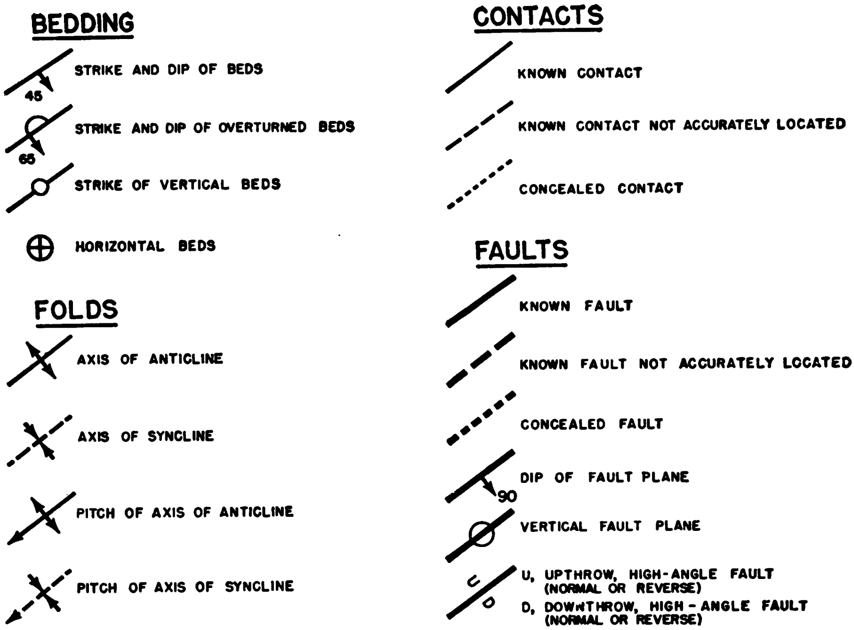



*Figure 98. Conventional structural symbols.*

*c. Geologic Sections.* Geologic maps often carry one or more *geologic sections* as marginal data. The section is a graphic representation of the disposition of the various strata in depth along an arbitrary line, usually marked on the map. Geologic sections are, at best, somewhat hypothetical, and must be used with caution. The vertical scale is nearly always exaggerated although this fact will be indicated in the legend. Also, sections prepared solely from surface data may easily be erroneous and should be used only in a general way. Sections prepared from drilling records or mining evidence may, on the other hand, prove entirely reliable. A section compiled from information obtained in one small locality is called a *columnar section* and shows only the succession of strata and not the structure of the beds as does the geologic section.

*d. Types of Geologic Maps.*

(1) *Bedrock or areal geologic maps.* A geologic map showing a plan view of the bedrock in the area is a *bedrock* or *areal geologic map* (app. II). Such a map indicates the boundaries of the visible formations and the inferred distribution of

those units covered by soil or plant growth. Areal maps do not show soil or unconsolidated mantle except that they usually indicate thick deposits of alluvium. In areas of complex geology where exposures of bedrock are scarce, the location of the contacts between formations is often only approximate or hypothetical and is so indicated. Areal geologic maps are commonly accompanied by one or more geologic sections. Again, the accuracy of these sections is dependent on the nature of the geology of the area and on the number of bedrock exposures available for study.

(2) *Surficial geologic maps. Surficial geologic maps* differentiate the unconsolidated surface materials of the area according to their geologic categories, such as stream alluvium, glacial gravel, and windblown sand (app. III). These maps indicate the areal extent, characteristics, and geologic age of the surficial materials.

(3) *Structural geologic maps.* Areal geologic maps of moderately deformed areas often carry enough structure symbols to provide an understanding of the structural geology of that region. In highly complex areas, however, where a great amount of structural data is necessary for an interpretation of the geology, special *structural geologic maps* are prepared. These maps are more complete in their coverage of the structural details of the region and have many symbols to represent the characteristics of folds, faults, joints, and the different kinds of flow structures. Often larger symbols are placed on the map to indicate the general trend of the individual observations. These maps also may show *structural contours* and *isopachs.* Structural contours are drawn on the top of a particular bed or stratum; isopachs are lines which connect points of equal thickness of a particular bed or stratum. Both require detailed subsurface data obtained by drill records or mining. Structural geologic maps are particularly useful for interpreting ground-water supply and conditions for underground installations.

*e. Interpretation of Geologic Maps.* In addition to giving the age of the mapped rocks, some maps give a brief description of the rocks. Many maps, however, lack even a brief lithologic description. The experienced geologist can make certain assumptions or generalizations from the age of the rock alone, by making analogy with other areas

over the world. For example, he can assume that Tertiary rocks, because they are young, are likely to be soft and poorly consolidated, or that Permian "red beds" are likely to contain gypsum. For more certain identification of the lithology and for details, geologic literature on the area must be consulted. Geologic reports of the country are valuable for making engineering estimates because they may be able to provide such information as structure, geologic history, and water-bearing and physical properties of the rocks. Some of the geologic reasoning that goes into an engineering interpretation of maps is outlined in paragraphs 58–61.

## 55. Secondary Sources of Geologic Information

*a. Soil Maps and Reports.*

(1) Soil maps show the areal extent of soil units that are classified on the basis of the characteristics of the different soil horizons and the texture of the surface soil. The soil separations usually are made with an agricultural rather than an engineering aim, so it is usually necessary to interpret the information and sometimes to reclassify or regroup the units. To undertake this, the interpreter should be familiar with both the agricultural and the engineering soil classifications.

(2) If soil maps and reports are available in addition to geologic maps, they can be used to amplify the details of the ground interpretation, for several soils having important characteristic differences may be present on one geologic formation. For example, an area which is shown on a geologic map simply as alluvium may include such widely diverse forms as sandy natural levees; gravel bars; silty, clay bottomland; and organic deposits in swamps. These would all be shown separately and in detail on a soil map.

*b. Topographic Maps.*

(1) The contours of topographic maps, especially when the contour interval is 20 feet or more, tend to give only a generalized view of the land surface. For example, sharp irregularities in the land surface may appear on the map as smooth elements; and some important features such as ravines, low escarpments, rock knobs, and sinkholes may not appear at all. When, however, a topographic map is used in conjunction

with a geologic map, geologic interpretations permit interpolation of features that would otherwise not appear.

(2) Through geologic inference, topographic maps may yield considerable information other than topography. Inspection of the pattern of the topography, steepness of slopes, and stream pattern can provide clues to the relative nature of the rocks, depth of weathering, soil, and drainage. For example, sinkholes may indicate limestone; hills and mountains with gently rounded slopes usually indicate deeply weathered rocks; and parallel ridges are commonly related to steeply folded, bedded rock with hard rock in the ridges. Features such as levees, sand dunes, beach ridges, and alluvial fans can be recognized by their characteristic shapes and geographic location.

*c. Aerial Photographs.*

(1) Aerial photographs are most useful and reliable when they are used in conjunction with other information or with ground investigation.

(2) The most satisfactory results are obtained from large-scale photographs, 1:15,000 or larger. Some topographic features, such as some ravines, rocky knobs, and sinkholes, are too small to be shown on maps. These features, as well as the larger topographic forms such as stream channels and swamps, can be observed directly from aerial photographs.

(3) Such surface features as glacial drift or eskers are easily recognized on aerial photographs. The presence of permafrost and ground ice can be determined by the identification of such features as thermokarst lakes and polygonal ground. Recognition of sand dunes not only indicates the texture of the soil but also provides a clue to the prevailing wind direction.

(4) Some geologic structures (figs. 85, 88, and 94), can be easily identified from aerial photographs.

*d. Miscellaneous Sources.*

(1) Local authorities and technicians, such as surveyors, engineers, miners, contractors, and quarrymen, may provide useful data on the local geology and engineering problems, kinds and types of rocks and soil in the area, and locations of available exposures or deposits.

(2) In foreign countries, the best and most accessible sources of maps, in addition to the United States military maps, are the

national, state, or provincial geological surveys. Many symbols and conventions used on geologic, soil, and topographic maps are universal or nearly so, although others are quite different. Topographic and geographic features are designated in the language of the country producing the map. For detailed treatment of the maps of foreign countries, see TM 5–248.

(3) For some little known areas, even topographic maps may be lacking, and interpretations of the geology may have to depend on such sources as coastal pilots, explorers, or missionaries.

## Section III. INTELLIGENCE REPORTS

### 56. General

*a.* Intelligence reports of various types are usually available for most areas where military operations have been anticipated. Such reports range from small-scale summaries of large areas to large-scale, detailed coverage of small areas or selected sites. The small-scale summaries are intended for high-level strategic planning and are suitable for background information only. The large-scale studies are intended for operational use. If only the small-scale broad studies are available, they may be used on the ground, if their limitations are kept in mind.

*b.* One of the best and most complete sources of geologic intelligence in foreign areas is the series of Terrain Intelligence Folios prepared by the Intelligence Branch of the Corps of Engineers, in cooperation with the U. S. Geological Survey. These folios and other studies prepared by the United States armed forces or allied armies can provide interpretations on terrain evaluation, water supply, and various engineering problems.

### 57. Uses of Intelligence Reports

*a. Terrain Evaluation.* Terrain studies analyze the land by subdividing it into *terrain units* so the general operational problems common to each unit can be described. These problems include movement and cross-country trafficability for vehicles, river crossings, cover, concealment, water supply (par. 178), airfield sites, road alinements, and possibilities for hasty excavations and "digging-in" (fig. 99). Paragraphs 58–61 and 62–85 give detailed information on terrain problems.

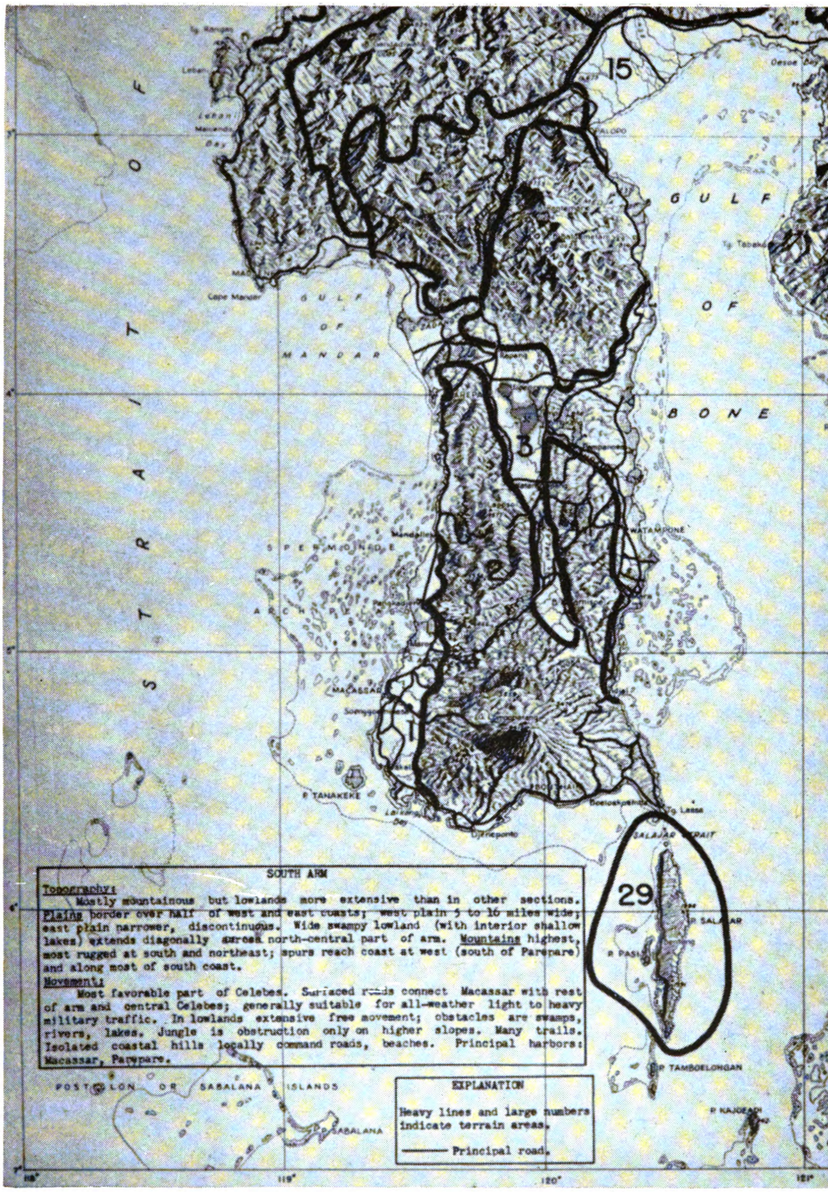



*Figure 99. Sample of terrain summary map from strategic engineering study of the Celebes.* **(Numbered units were discussed in an accompanying text).**

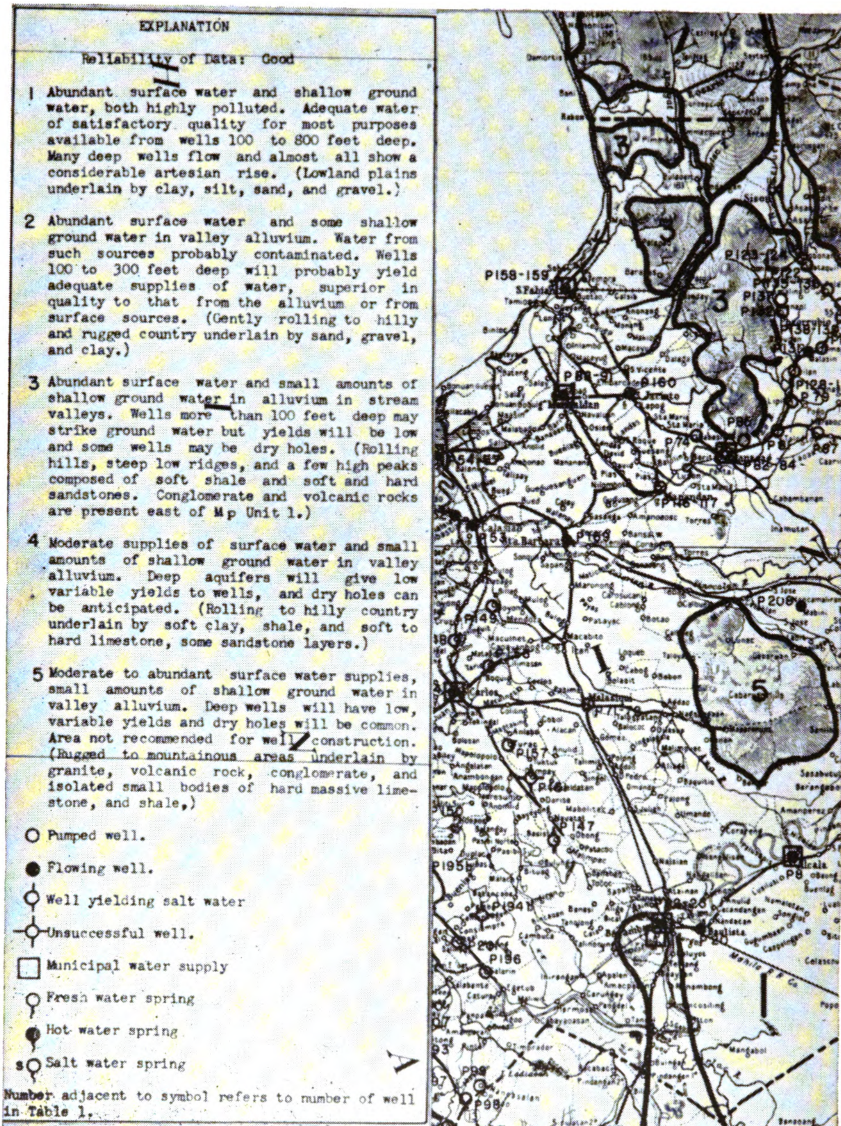



*Figure 100. Sample of water supply map from strategic engineering study of Central Luzon, Philippine Islands.* **(Data on individual installations were listed in an accompanying table).**

*b. Water Supply.* Special itelligence reports or sections of intelligence reports cover availability of surface and ground water (fig. 100). Existing and potential supplies are evaluated as to the location of reservoirs, springs, and wells; possibilities for use of other surface sources; and drilling of new wells. Quantities available at single water points and the chemical, mineral, and bacterialogical quality are reported or estimated. Unique problems may be described, such as the development of fresh water sources on beaches.

*c. Engineering Problems.* Detailed intelligence reports on individual engineering problems cover such subjects as suitability of an area for construction of roads and airfields, maintenance problems that might be expected, suitability for construction of underground installations, and availability of natural construction materials. The reports select and evaluate possible sites and estimate grading, foundations, drainage, and clearing. They may cover special engineering problems, such as those arising in areas of permafrost, laterite, or coral reefs.

## Section IV. APPLICATION OF MAPS AND LITERATURE TO THE PREPARATION OF INTELLIGENCE REPORTS

### 58. MAPS AND TERRAIN DIAGRAMS

This paragraph shows how a geologic analysis can be made by studying topographic and geologic maps and terrain diagrams. It illustrates the high degree of detail that can be inferred with the aid of geology where ground reconnaissance is not possible.

*a.* Figure 101 is a topographic map showing the elevation contours in an area containing about 2⅝ square miles in an arid section of southwestern United States. Figure 102 is a sketch made from a mechanical projection of the contour map. The sketch, drawn to correspond exactly with the relatively smooth contours of the topographic map, shows how the shape of the surface might be visualized by someone who had no information as to the geology or the characteristic topography of such areas. The projected contours have been placed on the sketch to show the control from which the sketch was made. These do not necessarily have to be included. Figure 103 is a materials map showing the distribution and kind of materials exposed on the surface or located immediately below the surface soils. The materials map and description below the map are compiled from geologic data. Figure 104 is a terrain diagram showing what is

believed to be the true appearance of the land in this area. The appearance is inferred by combining the data on the topographic map with those of the materials map. On a more accurately drawn contour map, some of the geologic data could have been inferred without the materials map. No matter how good the topographic data, geologic data will provide additional information.

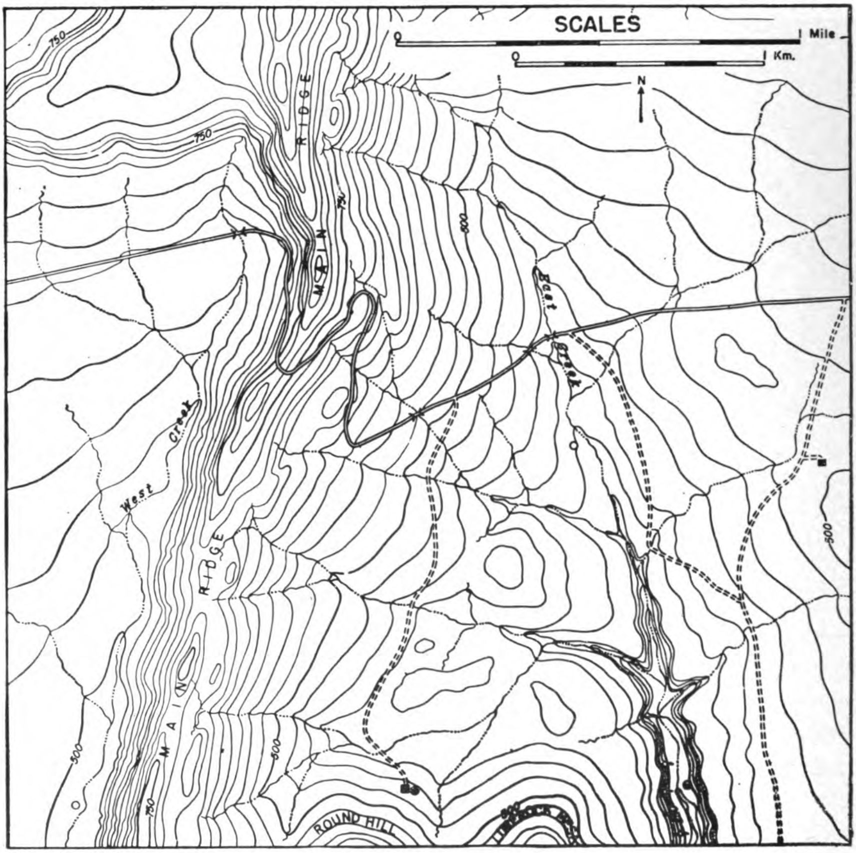



*Figure 101. Basic map, topography.*

*b.* In figure 103, formation A is alluvium, which is known to be less than 50 feet thick. According to the information given, the alluvium is loose and made up of layers of gravel, sand, silt, and clay, partly interlayered and partly mixed together. The fragments composing

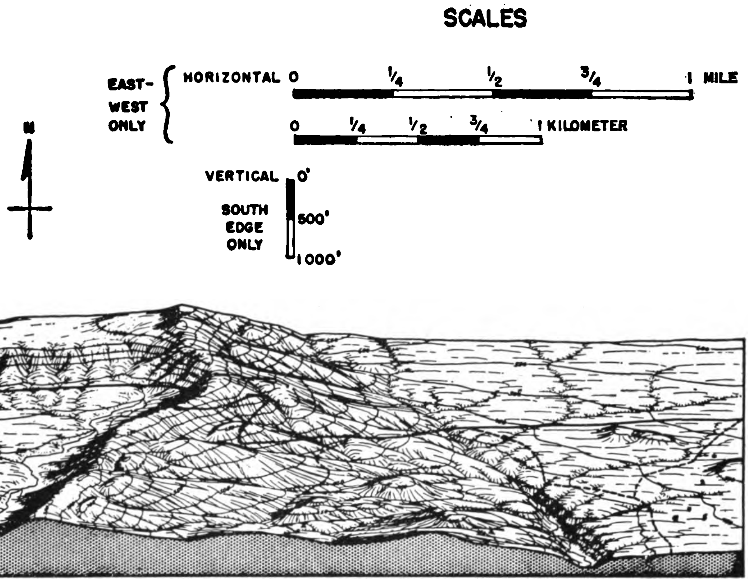
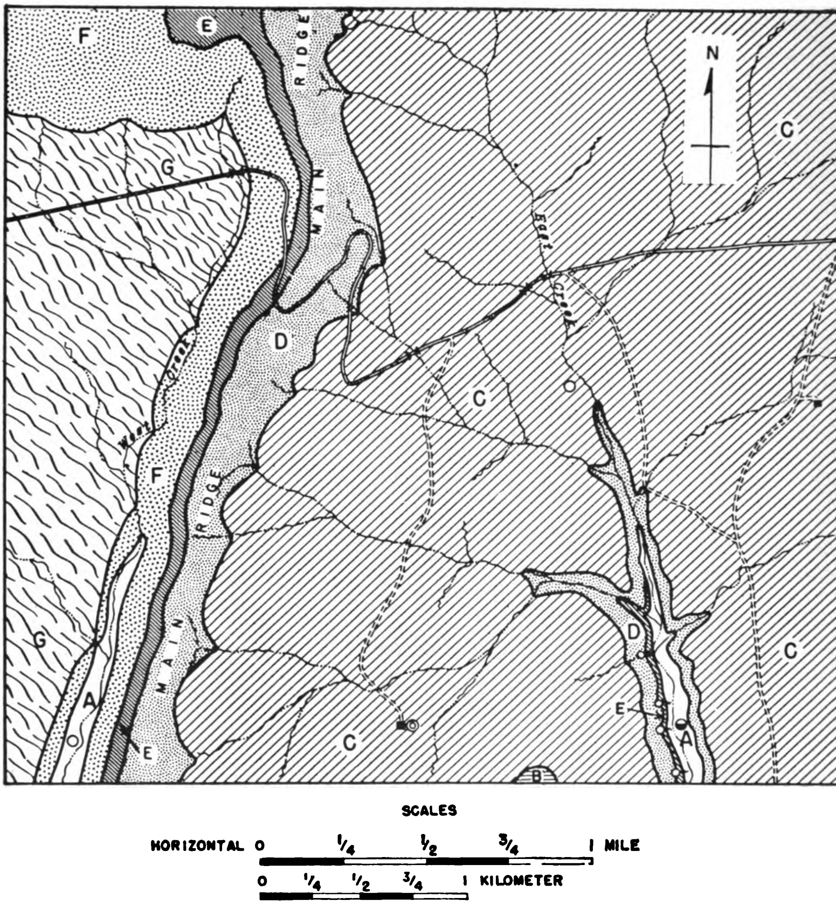



*Figure 102. Terrain diagram sketched from mechanical projection.*

the alluvium come from older rock formations, but the formation they now compose is the youngest in the area in point of age. The alluvial deposits in East Creek and West Creek are considered parts of the same formation. The smaller streams have not yet made deposits large enough to show on a map of the scale used.

*c.* Formation B is a layer of hard limestone, capping Limerock Mesa and known to have a maximum thickness of 45 feet. Note that the contour map does not show a ledge around the top of this hill. Its presence is deduced, however, from the fact that the hilltop is limestone. It is known that limestone is resistant to weathering and erosion in dry climates; therefore, it will probably form a ledge. The limestone cap on this hill, or mesa, is a remnant of an extensive limestone layer that has been removed elsewhere in the area by erosion. The softer rock (shale C) under the limestone ledge would normally be eroded faster than the limestone, and in this way the ledge may be undermined. Blocks of limestone would then lose their support and, from time to time, fall down the slope. These blocks would be gradually broken up by weathering. The wash from occasional rains would move the blocks down the hill inch by inch. On a gentle slope the blocks would move slowly, and over a long time would be broken into small




## DATA CONCERNING SURFACE MATERIALS

| SYMBOL | KIND OF MATERIAL | THICKNESS IN FEET | TOPOGRAPHIC EXPRESSION | DISTINCTIVE FEATURES | WATER-BEARING PROPERTIES |
|---|---|---|---|---|---|
| A | Alluvium; gravel, sand, silt, some clay. | 50 | Flood plain and valley bottoms. | Unconsolidated | Permeable, small underflow; year round yield only where underlain by impervious rocks. |
| B | Limestone. | max. 45 | Caps flat-topped buttes. | Thick massive beds; hard; resistant. | Impervious. |
| C | Shale; kaolin type clay shale; lower 50′ is sandy shale interbedded with sandstone in beds up to 20′ | 200 | Low hills; lower sandy beds form minor ridges on east slope of Main Ridge. | Clay shale is finely laminated, easily eroded; sandstone is hard. Sharp contact with limestone above. | Shale impervious; basal sandy beds slightly permeable, very small yield. |
| D | Sandstone: quartz-sandstone with lime cement. | 125 | Forms crest of Main Ridge | Fine-grained; thick massive beds; resistant. | Low permeability; small yield; water is high in carbonates. |
| E | Shale; gypsum bearing shale containing shaly sandstone lenses and pure clay layers. | 200 | Forms broken slopes along East Creek and west side of Main Ridge. | Sandstone lenses are fine to coarse-grained; poorly cemented. | Shale impervious; sandy beds slightly permeable; water is brackish. |
| F | Sandstone | 250 to 300 | Moderately resistant; hard beds form ridge along West Creek valley and cap northwest upland. | Coarse-grained (in part containing pebbles up to 1″ diameter); poorly cemented; some hard, resistant beds. | High permeability; large yields; water is low in dissolved minerals. |
| G | Schist: mica bearing rock cut by irregular quartz veins. | 800 + | Forms western lowland. | Finely laminated in general; a few massive granitic layers. | Impervious; no water except in occasional open fissures within 200 ft. of surface. |

*Figure 103. Basic data concerning surface materials.*

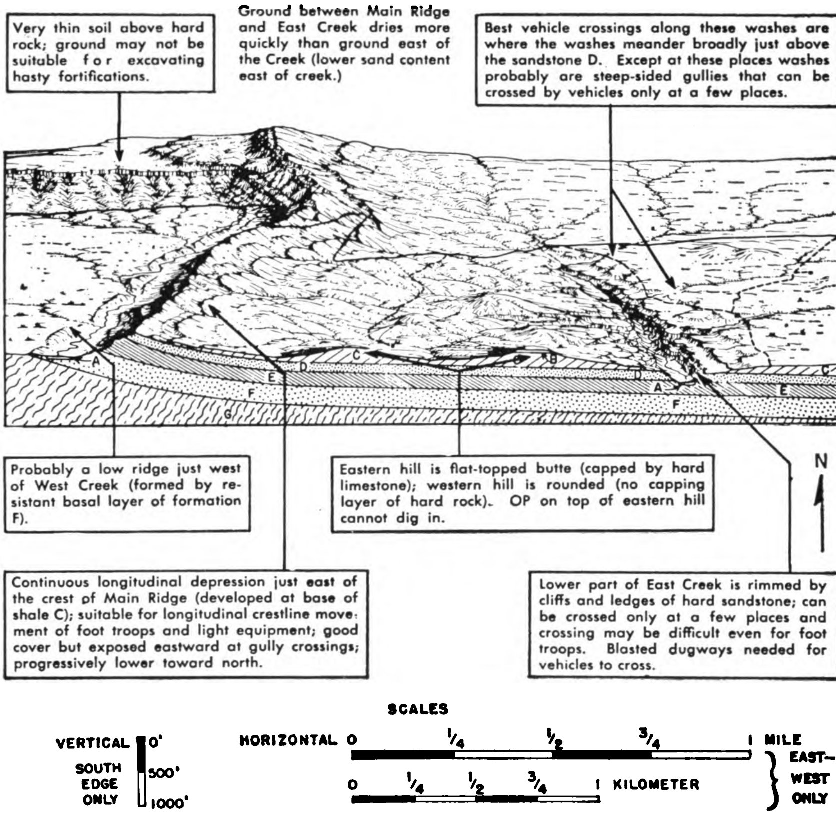



*Figure 104. Terrain diagram prepared by combining geologic and topographic information.*

particles before reaching the alluvium. On a steep slope, they would move faster and might reach the bottom as blocks. Considerations like these are sometimes used in estimating the probable character of an alluvial deposit as a source of aggregate for roads.

*d.* Formation C is a layer of clay shale known to be about 200 feet thick. The lower part is known to be sandy, with some beds of sandstone. Sandy shale is often harder than shale, and sandstone may be harder than either. If any evidence exists that this possibility applies to this sandstone, it may be inferred that outcrops of these beds will form ridges since the harder rocks stand out in relief because they do not weather away as rapidly as those with which they are associated. In figure 101, the contours indicate a number of subdued forms just

east of the crest of Main Ridge. The materials map shows that these forms coincide with the outcrops of the lower part formation C. These features, therefore, probably represent resistant sandstones in formation C. Since these layers are continuous in the area in which the basal beds of formation C are exposed, the existence of a fairly continuous ridge may be inferred as shown in figure 104.

*e.* Formation D is thick-bedded (massive), hard sandstone, known to be about 125 feet thick. Its high resistance to erosion is clear from the fact that its outcrop forms the crest of the highest ridge. A ridge of this kind is called a hogback. If the shale C were the more resistant, erosion would cause its outcrop to stand higher, and form the crest of the ridge. The sandstone D can be assumed to form sharp bluffs in the canyon of East Creek, a condition not shown by the contours of figure 101.

*f.* Formation E is shale which contains some harder sandstone beds and is known to be 200 feet thick. It is exposed on the west side of Main Ridge and in the canyon walls of East Creek. The sandstone ledges may be assumed to protrude from bluffs, as a result of erosion, and to form the steepest parts of the broken slopes.

*g.* Formation F is another sandstone, somewhat softer than sandstone D and known to be 250 to 300 feet thick. Hard beds at the base of this formation would be expected to form a low ridge west of West Creek, not shown by the contour map but readily inferred from the information that they are hard. A hard bed near the top of the formation caps the upland in the northwest.

*h.* Formation G is composed of micaceous schist, a fairly hard, platy, metamorphic rock that is much older than the overlying sedimentary formations and is known to be over 800 feet thick.

## 59. TECHNICAL STUDY OF TERRAIN

*a.* An analysis of the topography with the aid of geologic principles constitutes what is commonly referred to as a technical study of terrain. when such a study is prepared for military use, the study is presented in the form of a report that contains a concise description of the area (par. 60) and appropriate appendixes (par. 61). When conditions warrant, a partial report may be prepared consisting of an annotated or overprinted photograph or map unaccompanied by a written section.

*b.* The purpose of a technical study of terrain prepared for military use is to:

(1) Present the topographic aspects of an area as interpreted by the application of scientific principles, especially those of geology and soil science.

(2) Present the technical information in the form of a clear, concise written report illustrated with sketches and photographs which can be used by staff officers and the unit commander in planning and making decisions. Specific elements which may be of immediate interest, such as sources of road aggregate or ground water, can be emphasized as may be required. An example of the type of a sketch that might be included in such a report is shown in figure 104.

## 60. General Description of the Area

The first step in the preparation of the written report is to describe the area. The description includes a concise summary of the following four factors, which determine the appearance of an area.

*a. Relief and Drainage.* Relief and drainage conditions can be determined from the sources, described in section II. The features of relief and drainage of greatest tactical interest are the existing limitations on concealment, defilade, fields of fire, observation, and movement for individuals and weapons.

*b. Vegetation.* Vegetation present in the area can be determined from aerial or ground photographs, ground or air reconnaissance, personal experience reports, travel literature, and botanical literature. The information accumulated from these sources should be evaluated from two viewpoints; how the vegetation affects concealment and how it affects movement of military personnel and equipment. In the arid region illustrated in figure 104, the vegetation is assumed to be similar to that in other arid regions, and to be very light, consisting of low grass with scattered scrub growth along streams. Aerial photographs could be used to confirm this inference.

*c. Surface Materials.* Surface conditions can best be determined from soil (survey) maps, geologic maps, aerial photographs, technical journals, and texts. Surface conditions should be studied with respect to their effect on trafficability and the construction of field fortifications. These data should be combined with weather information to include all possible variations in conditions. In areas where the pertinent reference sources are not available, soil conditions can be inferred from these of adjacent areas. Also, soil conditions can be inferred

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by using geologic principles and topographic and climatic information. Referring to figure 104, the soil developed on shale C will have a high proportion of clay and will contain some sand west of East Creek where the parent shale is sandy. Formation G is a type of rock that is known to form micaceous clayey soil, hence the existence of such soil can be inferred where this type of rock is at the surface. The soil on Main Ridge, derived from pebbly sand rock, is sandy and pebbly. No soil remains on the steep rock outcrops because it is washed away as fast as it forms.

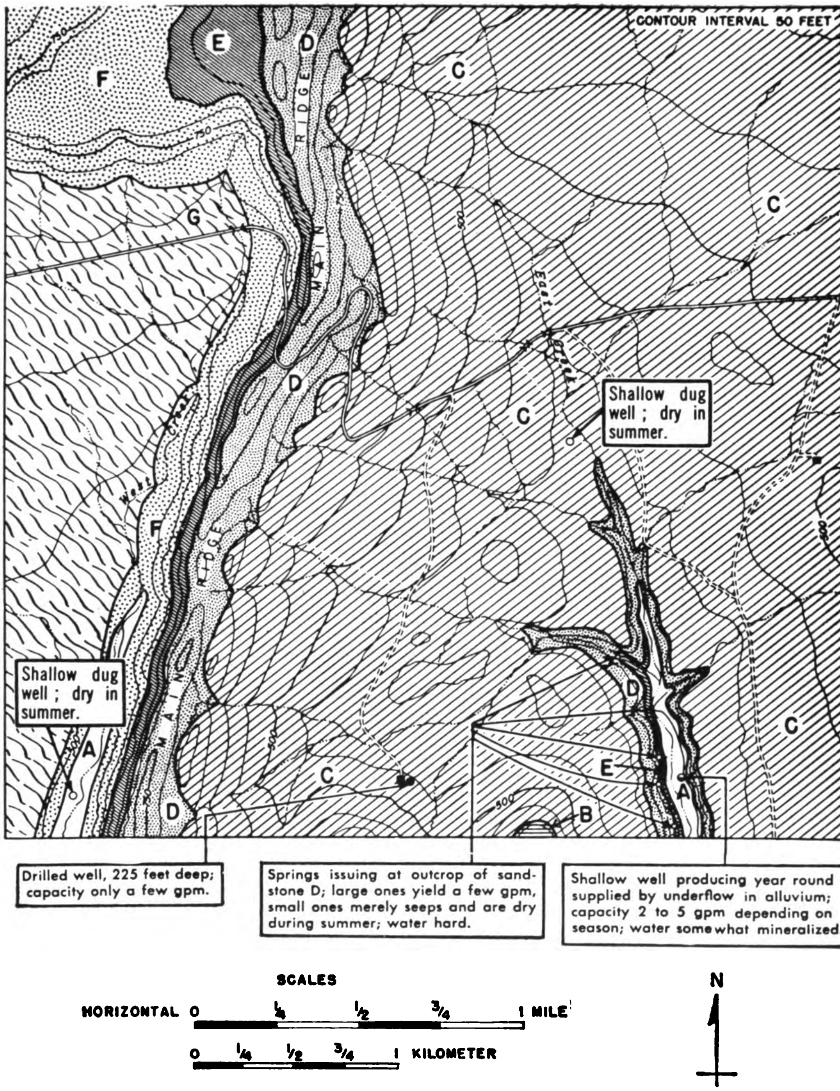
*d. Cultural Features.* Cultural features include paths, trails, roads, railroads, airfields, bridges, tunnels, shelter, utilities, built-up areas, farm areas, and fortified areas. The sources of this type of information are maps, aerial and ground photographs, reconnaissance, and various types of literature. All of this information should be interpreted with respect to its effect on the tactical situation. The analysis should include not only an estimate of possible damage but also probable use of the features, by both enemy and friendly troops.

## 61. Technical Appendixes

Specific aspects of a technical study of terrain are covered in the technical appendixes. Technical appendixes that can logically be attached to a technical study of terrain will depend on the situation. They normally would include the following:

*a. Trafficability.* Wheeled and tracked motor vehicles can move without much trouble over the flats and gentler slopes between gulches. Vegetation is no hindrance. During rains, the soil on shale C and that on schist G, both being clayey, will be very slippery and will hamper the movement of vehicles. Because of the hot, dry climate, the ground will certainly dry quickly after rains, especially between Main Ridge and East Creek where it is fairly sandy. Obvious barriers to movement are the canyon walls and the broken slopes of Main Ridge. The lower part of East Creek can be crossed by vehicles at only a few places, and approaches will have to be blasted; even foot troops will have trouble in many places. The best places to cross these streams are at points where they meander broadly just before crossing sandstone D. Note that both a road and a trail cross East Creek at this point. Stream currents will not hinder troop crossings except during the infrequent cloudbursts, which may cause flash floods.

*b. Local Resources and Construction Materials.* The sandstones




**West Creek and East Creek are intermittent streams; have small flow for several months during rainy season. Other streams flow only after heavy rains. Sufficient water for combat units is obtainable from springs throughout year and from streams during rainy season, but existing water is not adequate for permanent installations. Diagram on the next page shows how adequate supplies can be developed by utilizing ground-water.**

*Figure 105. Existing water supplies.*

on Main Ridge are probably a good source of aggregate for road construction. Sandstone D is harder and therefore more suitable than sandstone F. There is practically no overburden on the outcrop of this sandstone, and fresh rock faces suitable for quarrying are plentiful. Excavation would require drilling and blasting. The clay soil east of the ridge is a good source of binder for road metal aggregate; that on the west contains mica and is therefore probably too slippery for binder. The alluvium offers many sites for obtaining gravel and sand. (If no materials map were available, the presence of alluvium in the larger stream valleys could be inferred. However, with the materials map, the location and general composition of the alluvium is known.)

c. *Water Supply*. Since there is little rain, surface water must be scarce. The chart in figure 105 gives the available basic water supply

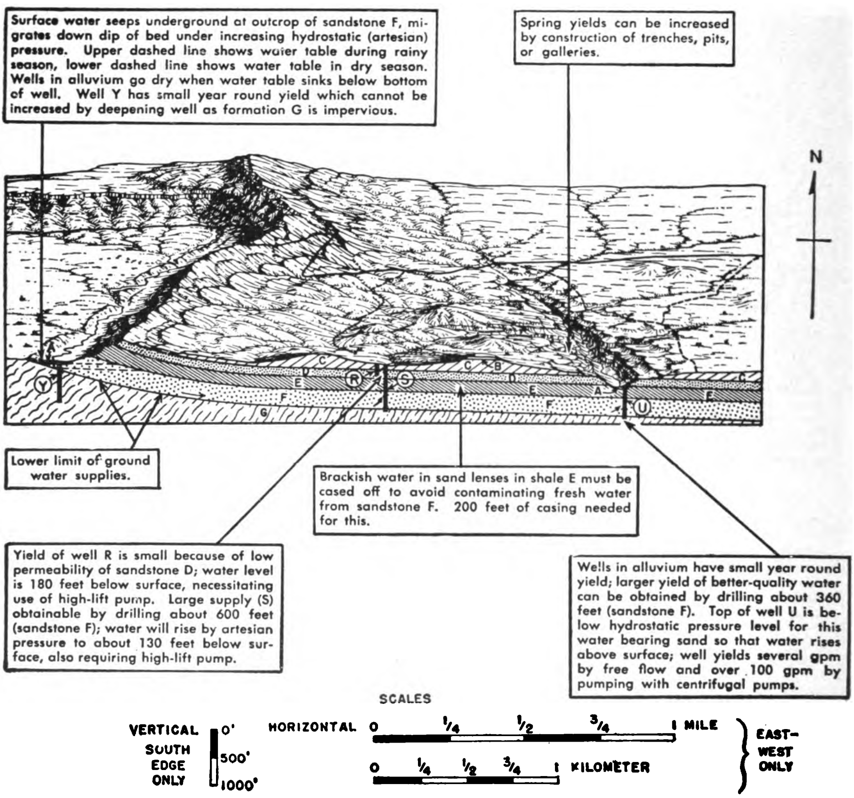



*Figure 106. Undeveloped water supplies.*

data. Small supplies are available from springs; West Creek and East Creek each has a small flow for several months during the rainy season, but not in the dry season. Other streams flow only after heavy rains. To develop large supplies of water, as required for a permanent installation, ground water must be utilized if and when available.

(1) In figure 106, note that the water from West Creek appears to seep underground into the outcrop of sandstone F. This water would normally migrate down the slope of the sandstone, which is known to be highly permeable. The water is confined in the sandstone by the impermeable shale above and the schist beneath. This sandstone is an aquifer which can transmit enough water to supply pumping wells or springs or, if the pressure head is sufficient, to flow from a well without pumping.

(2) If a shallow well were drilled into the sandstone D between Round Hill and Limerock Mesa (well R, fig. 106), the well would probably have a very small yield, and the water would probably be hard, for the sandstone has low permeability and is high in carbonates. Also, the water level would be expected to stand about 180 feet below the ground, and a high-lift pump would therefore be needed. If, however, this well were deepened to penetrate sandstone F, the yield would probably be much better, and the water would probably rise to about 130 feet below the surface. This estimate is based on the elevation of the water table in sandstone F near the outcrop on West Creek; the upper dashed line shows the height of the water table in the rainy season, and the lower dashed line its height in the dry season. This well would be expected to penetrate beds containing brackish water in sandy beds of shale E, and these would doubtless have to be cased off to prevent contamination of the fresh water from sandstone F. A maximum of 200 feet of casing would be needed for this purpose.

(3) A well in the bed of West Creek, drilled to sandstone F, would be expected to yield water during the rainy season, when the water table is high. During the dry season it would probably go dry, as the water table would sink below the bottom of the well. A deeper well (well Y) would be expected to have a small year-round yield from the schist,

but this yield probably could not be increased materially by deepening, since the schist has low permeability.

(4) A shallow well in the bed of East Creek would normally obtain a small year-round yield from the subsurface flow in the alluvium (underflow). Unlike well Y, however, this well could be greatly increased in yield by deepening to sandstone F, to a depth of about 360 feet. Besides, a much better quality of water would probably be obtained. As the top of the well is below the water level for this aquifer, the water would rise to the surface and flow under hydrostatic pressure. The well would probably yield several gallons per minute under free flow and over 100 gallons per minute by use of a centrifugal pump.

*d. Climate and Weather.* This appendix may be broken down into snow, ice, rainfall, and temperature, and may be obtained in whole or in part from the Air Weather Service, U. S. Air Force.

*e. Concealment and Cover.* Troops would have trouble digging in with hand tools in schist G or in the sandstone formation where the soil is thin and the underlying bedrock tough and hard, or on the northwestern upland, where a thin soil overlies hard sandstone. The same applies to Limerock Mesa. Round Hill and the area underlain by shale C would normally be easy to excavate with hand tools. Underground shelters would probably need to be blasted out of the bedrock in most places; they should be located on slopes well above the streams for the best drainage. (If underground facilities of any kind existed in the area they would be described as to the amount, type, structure, and hardness of the rock removed. An estimate of the difficulties to be expected in the construction of both large and small underground installations would be made.)

*f. Fortifications.* The location of pillboxes and gun emplacements is largely controlled by the location of possible enemy approaches.

*g. Effects of Bombing and Artillery Fire.* Shells or bombs falling on limestone B and sandstone D and F would form no craters, and might ricochet. Those falling on alluvium A or shale C would almost always form craters. Shells or bombs falling on schist C would not form large craters since the formation is fairly hard and the soil thin.

*h. Construction Problems.*

(1) *Structures requiring excavated foundations.* The information given in *e* above for constructing trenches, foxholes, or

underground shelters in the surface soils or rocks applies equally to structures requiring excavated foundations.

(2) *Ground Conditions Affecting Road and Airfield Construction.* On the clay soil west of West Creek, any road foundation would normally be unstable, and subject to shrinking and swelling. The soil there would probably be difficult to stabilize, even with aggregate. On Main Ridge, the soil is sandy and would require a binder, which could be obtained from the shale soil east of the ridge. East of Main Ridge, the soil is silty and grades to fine-sandy immediately west of East Creek. It would be more clayey east of East Creek. Both soils could be easily stabilized with aggregate taken from the ridge. An increasing amount of aggregate would be needed toward the east for the improvement of the road foundation. The possible airfield sites near West Creek have soil that is poorly suited to mechanical stabilization. In addition, adequate local water supplies cannot be developed. At possible sites in the northeast part of the area, the soil is suitable for stabilization, and adequate water supplies can be obtained by drilling.

# CHAPTER 4

# TERRAIN AND GEOLOGY

## Section I. GENERAL

### 62. Terrain

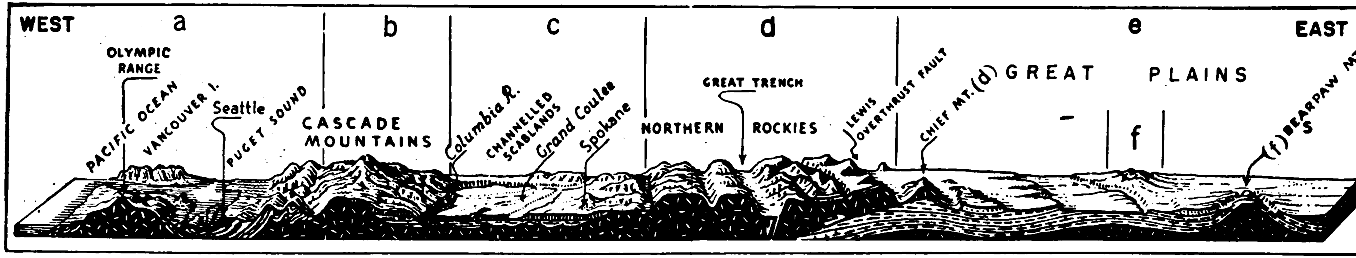
*a. Definition.* Terrain is an area of land considered as to its extent and natural features in relation to its use for a specific purpose. Terrain evaluation, or the application of knowledge of terrain features, is an important aspect of military operations since man's ability to operate militarily is affected by the character of the land.

*b. Factors.* The factors to be considered in making a terrain evaluation for military use are:

(1) *Landforms:* size, location, and distribution.
(2) *Drainage features:* size, characteristics, and location.
(3) *Ground:* nature of the rock and soil.
(4) *Vegetation:* kind, amount, and distribution.
(5) *Cultural features:* kind, amount, and location of buildings, roads, bridges, cultivated land, artificial terraces, or other man-made changes in the earth's surface.

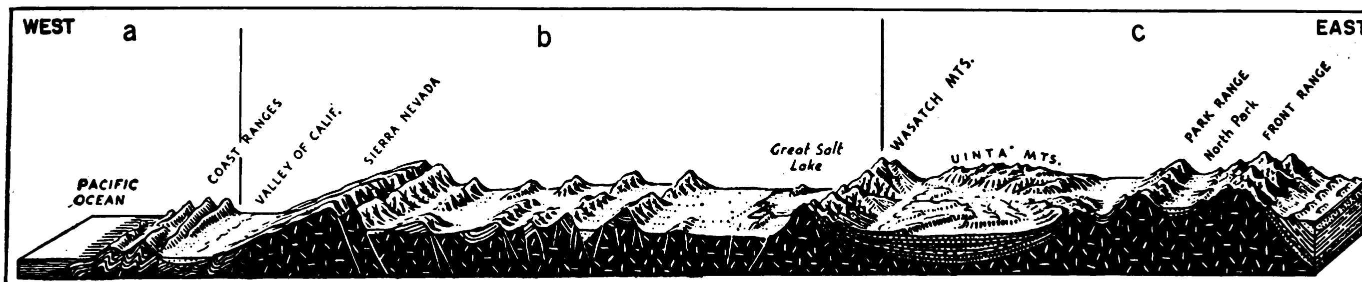
### 63. Relation of Terrain to Geology

Most terrain features are directly or indirectly related to the basic factors of geology and climate. Relationships of some of the common terrain types to the underlying geology are illustrated by examples shown on figures 107 through 110. The text description of terrain types shows the relationship. The terrain types discussed are rivers, which are major military obstacles; plains and plateaus, on which most large military operations take place; and hills and mountains, which are generally obstacles and in which operations of small units only are generally practicable.



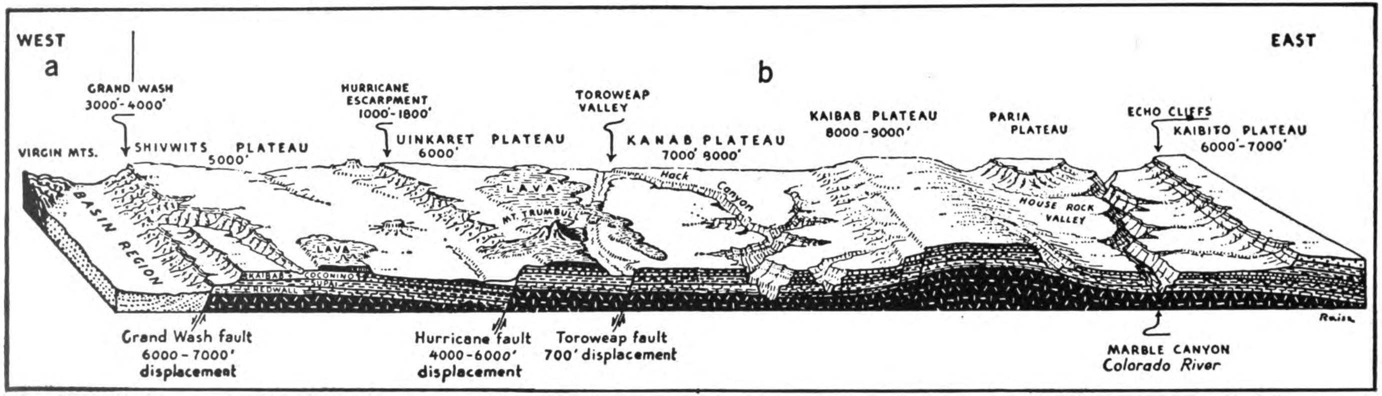

(From: "The Physiographic Provinces of North America," by W. W. Atwood, 1940, 1st. ed., Ginn and Company.)

*Figure 107. Diagrammatic structure section through northern Washington, Idaho, and part of Montana. a. Complex mountains and basins. b. Volcanic mountains. c. Dissected lava plateau. d. Complex mountains. e. Plateau. f. Dome mountains.*



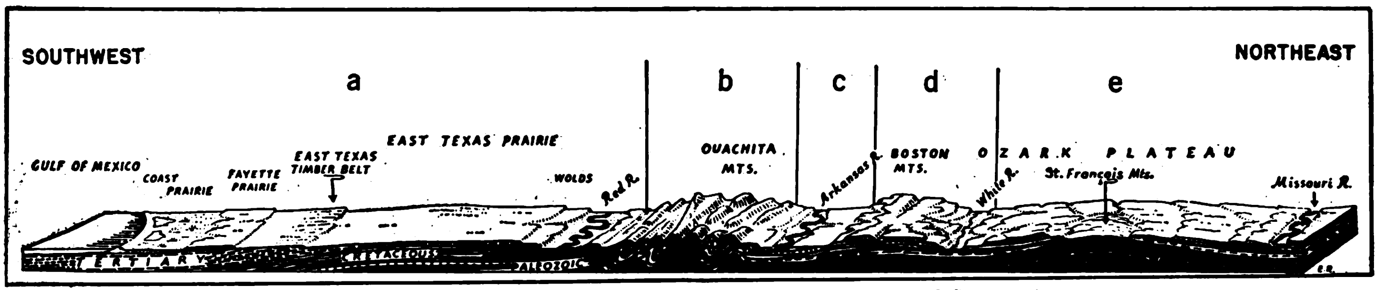

(From: "The Physiographic Provinces of North America," by W. W. Atwood, 1940, 1st. ed., Ginn and Company.)

***Figure 108.** Diagrammatic structure section near 40th parallel. a. Fold mountains. b. Fault block mountains and basins. c. Complex mountains.*




(From: "The Physiographic Provinces of North America," by W. W. Atwood, 1940, 1st. ed., Ginn and Company.)

*Figure 109. Diagrammatic structure section through the Colorado Plateaus. a. Fault basin. b. Dissected plateaus with lava plateaus in western part.*




(From: "The Physiographic Provinces of North America," by W. W. Atwood, 1940, 1st. ed., Ginn and Company.)

*Figure 110. Diagrammatic structure section through eastern part of Texas, Arkansas, and Missouri. a. Coastal plain with cuestas. b. Fold mountains. c. Structural valley. d. Dissected plateau. e. Domed uplift.*

## Section II. RIVERS

### 64. General

Large rivers have been of strategic and tactical importance since the beginning of military history. The success or failure of many campaigns has hinged on gaining control of a waterway, as the Mississippi in the Civil War, or in making a crossing like that of the Rhine in World War II. In terrain evaluation for both offensive and defensive operations, rivers are considered primarily as to the ease or difficulty of crossing. When no bridges or ferries exist, crossings depend on the size (width and depth) of the stream, velocity of the current, bank and bottom materials, stream pattern and shape, and time and duration of freezing. These factors, in turn, depend primarily on climate and geology, as brought out in the following paragraphs.

### 65. Size

*a. Factors Influencing the Size of Streams.*

(1) The size of streams is closely related to the amount of precipitation in an area, the largest streams occuring in regions with the greatest precipitation. Most of the precipitation finds its way to the streams either directly by runoff or from ground-water seepage into the channel. The proportion of the precipitation that will run off, sink in, and evaporate, and the rate at which these take place is in turn dependent upon other climatic factors, nature of the ground, vegetation, and slope. For example, in hot arid regions with porous ground, rivers may completely disappear by evaporation and seepage; in karst areas, rivers may disappear by entering underground channels.

(2) Seasonal fluctuations in stream size are related to the distribution of rainfall, snowfall, freezing and thawing. High water and floods occur at times of heavy rainfall and commonly during spring thaws. In and near mountains, where rainwater quickly collects in water courses, flash floods rise at the time of torrential rains. In some permafrost areas where ground-water sources are small or frozen, streams greatly decrease in size in the fall and even large rivers may freeze to the bottom in winter. Also in arid regions, fluctuations

are great because little ground water is available to maintain flow.

(3) High-water levels between periods of rainfall or during frozen periods may be maintained where there is sufficient ground water to feed the rivers.

*b. Effects of Size on River Crossings.*

(1) Fordability is determined in large part by depth. Large rivers can rarely be forded in their lower courses except where water is decreased by aridity or where the stream is braided. Fords may be picked across a braided stream by progressing from one bar to another, avoiding the deeper parts of the channels between. The line of movement may have to be diagonal or tortuous (fig. 111). In upper courses, where rapids and shallows are common, fords may be available in many places. Even in arid regions and in mountains, flash floods may prohibit crossing of an otherwise shallow or dry stream bed.

(2) In defensive operations, rivers can be made more effective barriers by increasing the size through destruction of dikes or dams. During World War II, the Allied advance to the Rhine was held up by flooding of the Roer River caused by enemy destruction of the large Schwamenthal Dam. The Yellow River and its valley was made a formidable obstacle by breaching its dikes.

## 66. Velocity

*a. Factors Affecting the Velocity of a Stream.*

(1) In general, the highest gradient and velocity are at the headwaters of streams, and these gradually decrease downstream. In the upper courses, streams are generally swift and rapids are common. Along the course of the stream, falls may occur where an obstruction exists. At the falls and for a short distance below the falls, the velocity is greatly increased over the average rate of flow. Near the mouths, rivers are commonly sluggish and a reverse flow may occur when tidal influence prevails. In general, velocities of streams increase at high water and decrease at low water.

(2) Variations in velocity occur within short stretches and between points across a channel. Flow is swiftest where the

stream is constricted; it is slowest where the stream can spread out broad and shallow. In a meandering stream, centrifugal force throws the water to the outside of the curves, so that the swiftest flow and the deepest part of the channel are near the outside bends. (fig. 112).

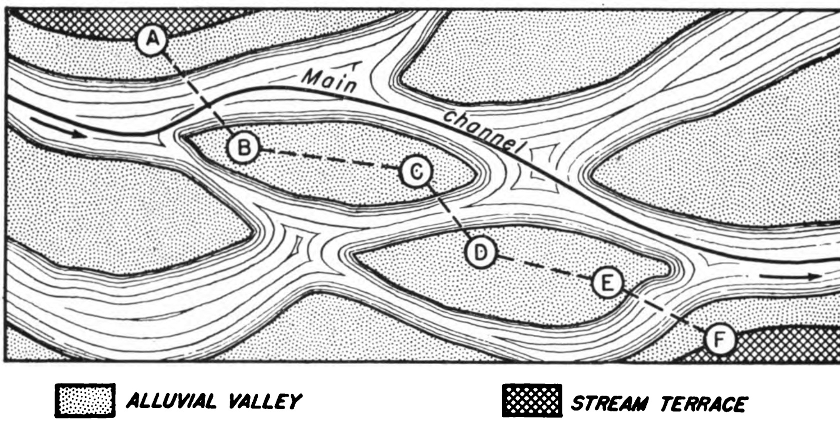



*Figure 111. Proposed crossing of a broad, shallow, braided stream.*

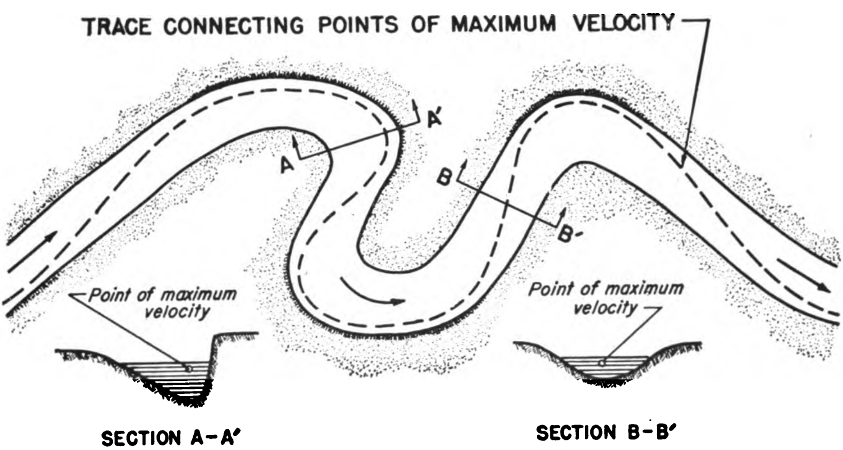



*Figure 112. Trace connecting points of maximum velocity a meandering stream at low water stage.*

*b. Effects of Stream Velocity on River Crossing.* The velocity of a stream is an important consideration for all types of crossings, whether by fords, bridges, or ferries. All are limited by swiftness of water. For

example, ponton bridges cannot be used safely when the velocity is more than about 11 feet per second; and bridge piers in soft materials can be disturbed by the scouring effects of rapidly moving water.

## 67. Bank and Bottom Materials

*a. Factors Influencing the Nature of Materials.*

(1) The materials of the banks and bottoms depend in part on the velocity of the stream. A swift stream in mountains may keep its bottom firm and scoured of fine, soft materials; a sluggish stream in a wide valley may dump large quantities of soft sand, silt, and mud that may pile up as bars and banks.

(2) Bank and bottom materials are progressively finer downstream. Rock and boulders occur in the upper courses, sand and gravel downstream, and silt, clay, and perhaps fine sand in the lower courses.

(3) The characteristics of bank and bottom materials also depend on the source rocks that supply the stream with sediment. For example, if the rocks of a drainage area are predominantly clayey (shale and slate), the stream will be muddy and the bed will contain little or no sand. Streams draining from glaciers or from a loess area carry and deposit much fine silt. On the other hand, if streams head in sandstone terrain, the banks and bottoms are likely to contain much sand.

*b. Effects of Bank and Bottom Materials on River Crossings.*

(1) Fording is difficult or impossible across bottoms with thick deposits of soft mud or silt. Sand bottoms may create difficulties where the sand is loose or where upwelling of water in the stream bed keeps the sand in a semi-suspended state (quicksand). If slippery, even a firm bottom may be unfavorable for crossings, especially if the stream is swift.

(2) Irregularities of the bottom are also an important consideration in fording. Bottoms composed of loose material continually change their configuration. The change is drastic at times of flood. Because of the change, fordable sections may shift from time to time.

(3) The slope, height, and firmness of banks affect bridge abutments and approaches to fords and ponton bridges. High, steep banks may be more favorable for span bridges than

for ponton bridges, and do not require long built-up approaches for spans as do low, gentle banks. High banks require cut approaches for fordings. Soft banks and bottoms may require deep pilings for bridge piers and abutments.

## 68. Stream Pattern and Shape

*a. Factors Influencing Stream Pattern and Shape.* The pattern of a stream system is determined by geologic history and structure. The individual stream, however, may have a single channel or several channels forming a braided pattern or forking as the distributaries in a delta. The stream alinement ranges from straight to curving to intricately meandering. These patterns and shapes are determined by the geologic age of the stream and of its valley, the gradient, the relationship of the erosional and depositional work of the stream, and the geology of the region (par. 27).

*b. Effects of Stream Pattern and Shape in River Crossings.*

(1) Crossings generally are more easily made across a straight stretch (reach) of a river. Bends are less favorable because of the greater variation across the channel in shape, velocity, and bottom conditions; the greater difference in height and steepness of the opposite banks; and the restricted maneuverability on the narrow land at the inside or concave bank.

(2) In crossing a broad, braided stream or a meandering river where many abandoned channels occur beside the main channel, troops can easily become lost or confused, or may incorrectly identify their positions.

(3) Because streams are obstacles, the pattern of a stream system is significant since it makes compartments of the terrain, presenting a series of crossing problems. Obviously, a number of channels multiplies the task of crossing.

## 69. Freezing

*a. Factors Affecting the Freezing of Streams.* The time and duration of freezing and thickness of river ice are primarily determined by climate. Other important factors include velocity and such unique situations as the presence of permafrost and other conditions conducive to formation of anchor ice, or flows of warm ground water into the channel that cause local areas of open water.

*b. Effects of Freezing on River Crossings.*

(1) When a river freezes it is no longer an obstacle. In regions of heavy forest or rough terrain, frozen rivers may become the most important routes for vehicular movement in winter.

(2) Along frozen rivers, local spots of thin ice or open water are hazards that should always be anticipated. Where ice is not sufficiently thick or strong for required loads, more layers of ice can be built up by spraying water or adding wet snow. Additional strength can be gained by incorporating timbers in such an ice structure. These methods were used effectively for crossing rivers in eastern Europe during World War II.

(3) Obstructions and narrows along a stream may create ice jams during spring thaw with resultant floods. This condition occurs along the Yukon River in Alaska.

## Section III. PLAIN AND PLATEAUS

### 70. General

*a. Description.*

(1) Plains and plateaus are lands of moderate relief ranging from level ground to undulating slopes and occurring at any elevation above sea level.

(2) Terrain where more than 50 percent of the topography consists of slopes that are less than 4° is defined as either plains or plateaus, but no clear-cut distinction can be made between them. A plain which is distinctly higher than the adjacent land or water on one or more sides, and slopes abruptly to the areas of lower altitude is called a plateau. Thus an extensive high plain bordered on one side by higher plateaus or mountains and on the other by lower plains may be designated either as a plain or as a plateau (*c* on fig. 107).

(3) On plains, relief is low and streams commonly flow in broad open valleys. Plateaus, on the other hand, have deep, narrow valleys or canyons (fig. 113) and may be bounded on one or more sides by an abrupt escarpment.

(4) Dissection of plains and plateaus may eventually become so advanced that the level surfaces virtually disappear. They may be succeeded by an intricate pattern of valleys and nar-

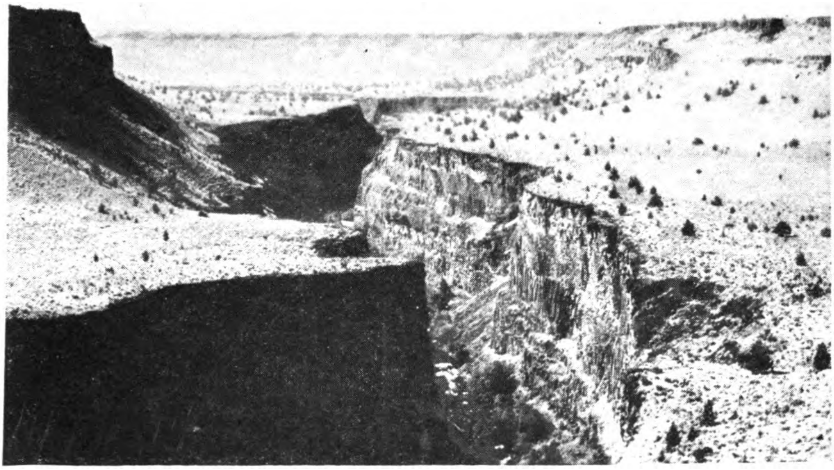


*Figure 113. Plateau in an early stage of dissection in a semiarid region. Crooked River, Oregon. Outer escarpment and edge of canyon are lava flows.*

row ridges. A high plateau may become so strongly dissected that a mountainous landscape results.

*b. Distribution.* Those portions of the world where the surface is largely plains and plateaus are shown in a generalized way on figure 114.

*c. General Military Aspects of Plains and Plateaus.*

(1) *Movement.* Although the relief of plains and plateaus rarely prevents movement of personnel and equipment, vegetation and poorly drained ground are serious obstructions. Steep to precipitous slopes along ravines, valleys, and escarpments are obstacles that tend to limit movement on the otherwise level surfaces. These features are especially well developed near the margins of plateaus.

(2) *Observation; concealment and cover.* Vegetation is particularly effective in limiting observation in plains and plateaus, where prominences that could provide commanding positions are generally lacking. In areas bare of trees, long distance observation is good, but cover, concealment, or defilade is poor except for that locally provided by low topographic forms such as escarpments.

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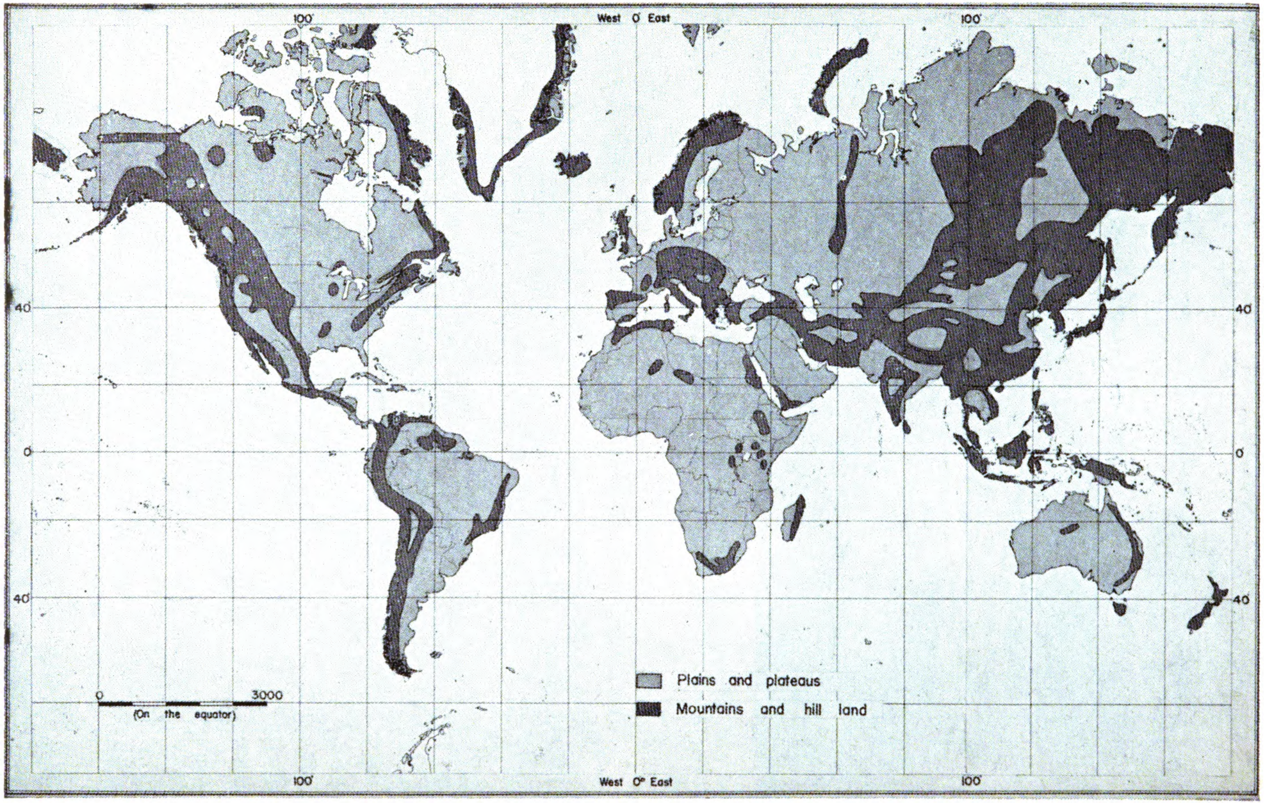


*Figure 114. World-wide distribution of plain and plateau and mountain and hill areas.*

(3) *Water supply.* The quantity of water available varies with the climate. As a rule supplies of surface and ground water are more easily obtained in plains and plateaus than in mountains.

(4) *Construction materials.* Plains and plateaus are better than hills and mountains as sources of sand and gravel, but not as sources of hard rock suitable for construction. Hard rock is exposed only locally and is less easily quarried. Some plateau escarpments, however, are excellent sources of construction stone in the form of such rocks as limestone and trap rock.

(5) *Construction problems.* Large airfield sites are almost entirely limited to plains and plateaus. Road construction is generally easier and alinements are much less restricted than in mountains. Foundations, however, may be poor because of bad drainage and the low bearing strength of soils. The ground is generally easily excavated but a high water table may limit the depth in many places. Well drained plateaus and terraces are excellent sites for large structures.

*d. Types and Variations of Plains and Plateaus.* Plains and plateaus may be formed through depositional or erosional processes or a combination of the two. Variations in appearance and landforms arise from differences in the materials that underlie the plains or plateaus, the geologic agents that deposited the material and the erosional processes that have taken place, and the climatic environment of the area. Some of the significant types and variations are described in paragraphs 71–82.

## 71. Coastal Plains

*a. Description.* Coastal plains are former parts of the sea floor that have been lifted above the present sea level, eroded areas partly submerged, or alluvial deposits built seaward from higher lands. Significant features for military operations are the shorelines, cuestas, sand dunes and beach ridges, and marine terraces. The origin and form of these are discussed in paragraphs 28 and 47.

*b. Distribution.* Coastal plains of various size are common on the margins of all continents and many islands.

*c. Military Aspects.*

(1) *Movement.*

(*a*) In general, the topography of coastal plains permits free movement of tracked vehicles. However, because of the unfavorable soil conditions and dense vegetation in areas of medium to heavy rainfall, trafficability, may be locally poor or impossible. Movement along an indented shore is difficult because of streams and estuaries that separate the land into compartments. Movement inland is limited to narrow land areas bordered by water. As a result, flank attacks are difficult or impossible without amphibious support and surprise is hard to achieve. The Peninsular Campaigns before Richmond, in the Civil War, are classic illustrations of the difficulties imposed by such terrain. Coasts with beach ridges hinder a direct advance inland, because vehicles are compelled to cross poorly drained areas between relatively stable sand ridges. Terrain of this type, common on the larger islands of the southwest Pacific, confines movement and prevents adequate dispersal of men and supplies. The sand dunes and the low, readily inundated land behind them along the North Sea coast of Europe are examples of obstacles to landing operations.

(*b*) In an otherwise nearly featureless coastal plain, cuestas are of great tactical importance. For example, a succession of eight semicircular cuestas, with their steep slopes facing eastward, have been used to protect the approaches to Paris from the east. To avoid these natural barriers, which have their maximum effectiveness near Verdun, the German Army twice invaded France from the northeast where the cuestas disappear near the sea: in World War I across Belgium and in World War II through the Forest of Ardennes. The objective of many of the historic campaigns in western Europe has been to exploit or avoid these concentric, asymmetric ridges.

(2) *Observation; concealment and cover.* The degree of observation on coastal plains is variable. Long stretches of the coast are generally open to view. Inland the flat country and forestation provide few observation points and limit observation to short distances. For example, in Normandy during World War II, the closely spaced hedgerows, which were planted between fields, successfully concealed the enemy

and limited the Allied advance to a hedgerow at a time. The cover provided by topographic forms is poor.

(3) *Water supply.* Supplies of surface and ground water are commonly adequate. On beaches a small amount of fresh ground water lies above the salt water (par. 174).

(4) *Construction materials.* Sand and gravel are abundant in beaches and along streams. Hard rock is generally absent.

(5) *Construction problems.* Numerous airfield sites exist and long, straight road alinements in various directions are possible. Marine terraces provided good locations for military air bases in World War II in Saipan, Tinian, Guam, Guadalcanal, Espiritu Santo, New Georgia, and many other islands in the South Pacific. The ground of coastal plains is generally easily excavated but depth of excavation is limited in many places by a high water table.

## 72. Delta Plains

*a. Description.* Deltas are accumulations of sediments dropped by streams where their velocities are abruptly checked, such as where they enter lakes or seas. The delta deposits are gradually built up to slightly above the level of the water bodies and form low, generally marshy plains (fig. 115). The features of military significance on delta plains include the shoreline, distributaries, lakes, swamps, marshes, and levees. The origin and form of these are described in paragraph 27.

*Figure 115. Distributary of Mississippi River flowing through a marshy delta plain.*

*b. Distribution.* Large delta plains are formed at the mouths of the main rivers of the world (fig. 116). Examples are the deltas of the Mississippi and the Volga. Large seaports built on deltas are

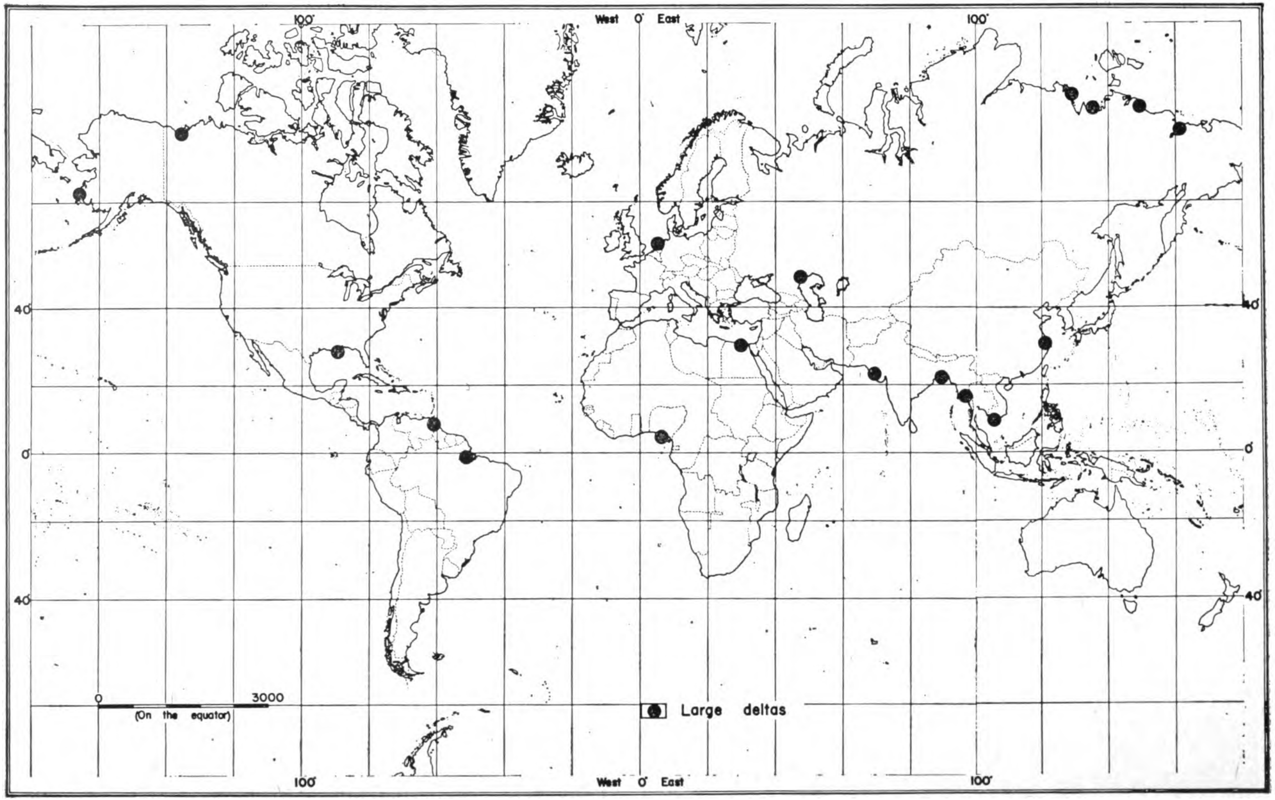


Figure 116. Large deltas of the world.

New Orleans, Rotterdam, Shanghai, and Rangoon. All are on low, poorly drained ground and all are exposed to periodic floods.

*c. Military Aspects.*

(1) *Movement.* Movement on delta plains is hindered by poor soil conditions of the marshy water-logged ground, the shifting streams with loose sand and mud bottoms, and the generally thick vegetation. Soils are better drained at the inner margin of the delta. The highest, best drained, and most trafficable parts of the delta plain proper are the natural levees adjacent to the streams. Deltas have been invasion routes for centuries, despite unfavorable terrain, because they give ready approach to the interior. The limitations of such terrain are illustrated by the 1815 Battle of New Orleans in which American positions on the natural levee could not be flanked because of a swamp on one side and the Mississippi River on the other. An ever present danger on the low lying ground of deltas is the possibility that dikes or levees may be cut by the enemy with resulting flooding. This was done in the Netherlands in World War II.

(2) *Observation; concealment and cover.* Observation is commonly limited on deltas because most of the low, flat ground is thickly covered by vegetation. Cover is lacking except for that provided by the levees.

(3) *Water supply.* Water is available in large quantities but may be of poor quality, in part brackish or salty.

(4) *Construction materials.* Sand and fine binder material are abundant, but gravel is scarce and ledge rock is absent.

(5) *Construction problems.* Location of airstrips and alinement of roads are generally confined to levees. Orientation of runways on levees is limited to the direction of the levees. Foundations of buildings and other structures not built on levees are unreliable because of the possibility of settlement on low, poorly drained ground and the danger of periodic flooding. Drainage is a serious problem. Since natural and artificial levees prevent flow into the river, cities sometimes construct elaborate canal systems and pump lifts to dispose of surface runoff.

## 73. Valley or Alluvial Plains

*a. Description.*

(1) Valley plains are formed of alluvium deposited by streams over their valley bottoms. The origin of valley or alluvial plains and the associated forms are described in paragraph 27.

(2) Unless protected by levees, the floodplain may become partly or completely covered by water in times of flood. It is commonly poorly drained and may contain marshes, swamps, lakes, and abandoned river channels in the form of sloughs or bayous (fig. 117).

(3) In old valleys the highest parts of the floodplain are generally the natural levees.

(4) The floodplains may be bordered by gently sloping alluvial fans or alluvial terraces which are generally the highest and best drained parts of the valley plain.

*b. Distribution.* Broad plains border the large rivers of the world. Valley plains may extend for some distance up the courses of rivers, forming a gradually narrowing ribbon of bottom land far into the

*Figure 117. Alluvial valley. Koyukuk River, Alaska.*

mountains where the rivers head. Examples of wide valley plains are those of the Mississippi, the Rhine, the Po, and the Yellow Rivers.

*c. Military Aspects.*

(1) *Movement.* Stream valleys are gently sloping corridors through areas of greater relief. In dry weather, movement is excellent, except for obstacles such as streams and local areas of poor ground and vegetation. In wet weather or during floods, movement may be limited to small areas of higher, better-drained ground, such as levees. Alluvial terraces are above flood levels and are consequently better drained than the floodplains. However, they are commonly isolated by steep slopes.

(2) *Observation; concealment and cover.* Observation on floodplains is variable. Observation on valley bottoms and out of valleys is poor, but bordering slopes provide commanding views into valleys. Cover is limited, but some is available along terrace scarps, river banks, and levees.

(3) *Water supply.* Water supply is abundant. Large amounts of surface water are obtainable on floodplains. Ground water is generally available at shallow depths on floodplains and at somewhat greater depths on terraces.

(4) *Construction materials.* Sand, gravel, and binder material are abundant and easy to obtain along stream channels and in terrace scarps. Hard rock is scarce in floodplains but may crop out along the scarps of terraces.

(5) *Construction problems.* Floodplains and terraces are generally well suited for construction of airfields and roads but foundations may be poor. Some of the best airfield sites are located on well drained terraces. An example is the airfield at Atsugi, Japan. In narrow valleys, orientation of runways may be limited to the direction of the valley. Excavations in floodplains are generally limited by the high water table. Terraces have good sites for large bunkers in many places.

## 74. Glacial Plains and Plateaus

*a. Description.*

(1) Glacial plains were created by the scouring and depositional action of large continental ice sheets. The ice scoured the bedrock, removing much of the soil in the areas beneath the

main glacial mass. As it melted, the ice sheet deposited a thick mantle of its transported debris near the outer margins of the glacial areas.

(2) Erosional (scoured) plains and plateaus are level to gently rolling areas composed of bare rock. They are dotted by numerous lakes which occupy scoured out, shallow depressions and portions of old valleys that were dammed by moraines (fig. 118).

*Figure 118. Glacial scour plains. Greenland. Note braiding in river channel in middle background.*

(3) Depositional plains with a hummocky surface of low relief may be underlain by several hundred feet of till that generally completely covers the underlying bedrock topography. Of military significance are such features as moraines, knob-and-kettle topography (fig. 119), eskers, kames, boulders and outwash (par. 29).

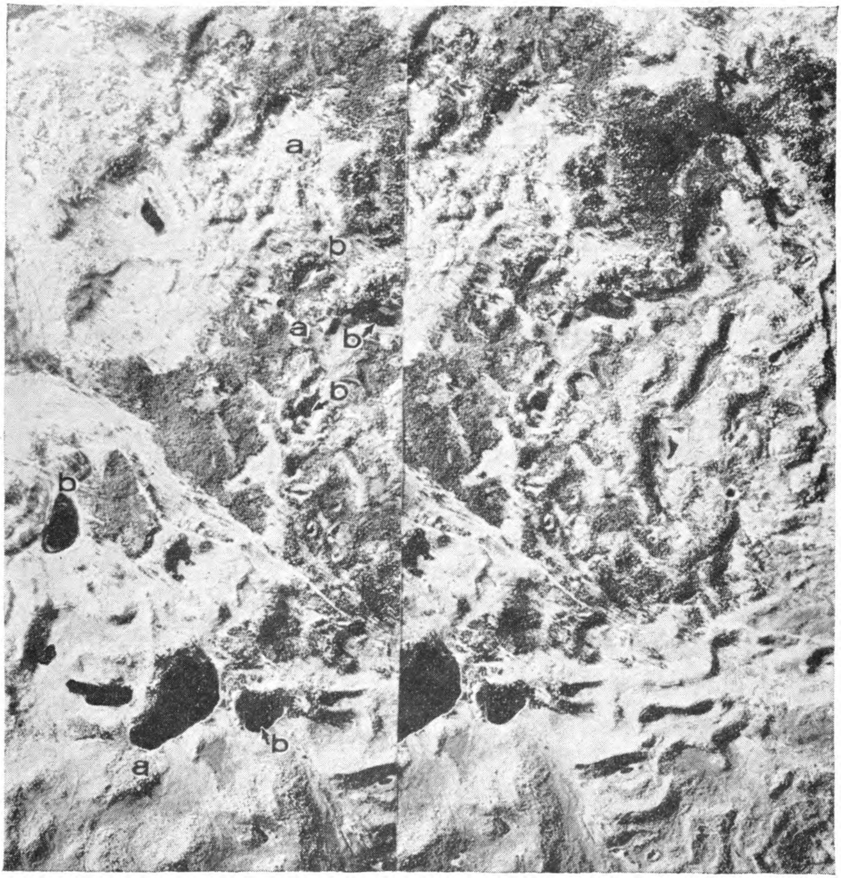


*Figure 119. Stereo-pair showing typical knob (a) and kettle (b) topography. Central Alaska, near Big Delta.*

*b. Distribution* (fig. 53). The northern half of Europe, parts of northern Siberia, and North America have extensive glacial plains. In North America they extend as far south as the Ohio and Missouri

Rivers, the scoured portion being the Laurentian Upland of Eastern Canada, and the outwash plains being in southern Illinois and Indiana. Well developed outwash plains are found in Poland and western Russia; glacially scoured plains occur in the Baltic shield of northern Europe.

c. *Military Aspects.*

(1) *Movement.* Large boulders may prove to be obstacles but, in general, the topography presents no insurmountable difficulties to movement. Prevalent soft ground, lakes, or marshes may seriously hinder movement. The broad, level outwash plains of Poland and western Russia have been invasion routes but in summer invaders mired down marshy terrain and in winter, when the ground was firm, they were defeated by the intense cold.

(2) *Observation, concealment and cover.* Observation on glacial plains is variable. Concealment and moderate cover are available in the more knobby and forested parts. Cover is lacking on the flatter parts, especially on the outwash plains. In cultivated areas, where vegetation does not interfere, observation may be good on the flat parts of the plains.

(3) *Water supply.* Supplies of surface and ground water are generally good.

(4) *Construction materials.* Sand and gravel are widely distributed. The best sites for pits are in kames, eskers, and outwash plains. On till plains, boulders can provide building stone but hard bedrock is available in only a few places, such as deep valleys where the overlying till has been cut through. Rock is abundant in the areas of glacial scour, where till is lacking.

(5) *Construction problems.* Many good airfield sites are available on the better drained parts of the plains, away from the knob-and-kettle areas. Road alinemnets are generally unrestricted. Wet ground and weak soils create foundation problems in many places. The ground is easily excavated. Large excavations can be made in the better-drained parts.

## 75. Lacustrine Plains

a. *Description.*

(1) Lacustrine deposits are sediments laid down on lake bottoms.

The smooth surface of the deposits becomes a lacustrine plain when the lake basin is drained or the water is evaporated.

(2) The surfaces of such plains generally are featureless and essentially level. However, if the lake was drained by a series of successive lowerings, the former margins generally show old shore features such as step-like terraces (fig. 120).

(3) Lacustrine sediments are mostly fine clay and silt. Some fine sand may be present near the old outlets.

(4) Lakes may occupy the lowest parts of some plains. They may be intermittent. Some are remnants of the larger lake that extended over the entire plain area, and are commonly salty or alkaline.

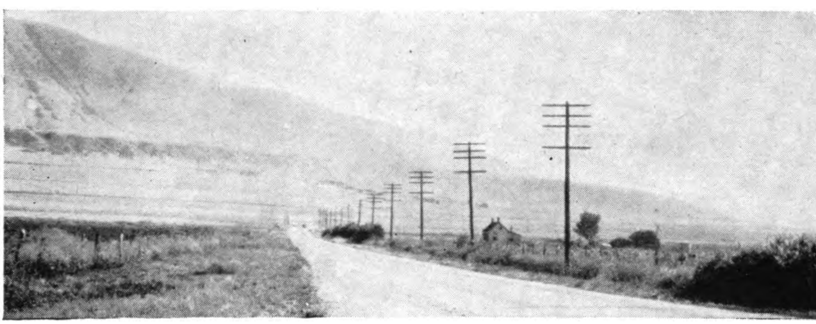

*Figure 120. Lacustrine plain near Great Salt Lake, Utah.*

*b. Distribution.* Large lacustrine plains are not common. Some of the largest are in northern North America, associated with past glacial activity. The largest of these is the former Lake Agassiz in North Dakota and Canada formed by the glacial damming of the Red River of the north. Great Salt Lake in Utah is the remnant of another much larger lake which formed the broad surrounding plains. Other lake plains occupy basins in Utah and Nevada. Small plains occur in northeastern Europe and in scattered parts of the world.

*c. Military Aspects.*

(1) *Movement.* The level plains offer no topographic obstacles to movement but the fine soils may be nontrafficable and slow drying during wet weather.

(2) *Observation; concealment and cover.* Observation is unlimited over the flat surfaces where trees are lacking, as is the case in the lake basins of the United States. Marginal

slopes provide commanding views into the basins (fig. 120). Cover is generally absent.

(3) *Water supply.* Surface water is absent or likely to be of poor quality. Wells may be satisfactory sources, but they may need to be deep and may yield water of poor quality.

(4) *Construction materials.* Except at the margins of the plains, where old beach sand and gravel and hard rock may be obtainable along bordering slopes, the plains can provide only clay and fine sand for construction purposes.

(5) *Construction problems.* Lacustrine plains are ideal airfield sites and unrestricted for road alinements, but the fine soil makes a poor foundation, particularly in humid climates.

## 76. Sand Plains and Plateaus

*a. Description.* Areas of wind-blown sand or sand dunes are

*Figure 121. Sand Plains. Algeria.*

common on arid plains and plateaus (fig. 121). The distinctive, irregular, hummocky topography of such areas is comprised of low swells and ridges, with intervening undrained depressions. The sand is commonly loose and shifting, but in many places dunes are stabilized by a mantle of vegetation (fig. 122). Origin and form of dunes are discussed in paragraph 30.

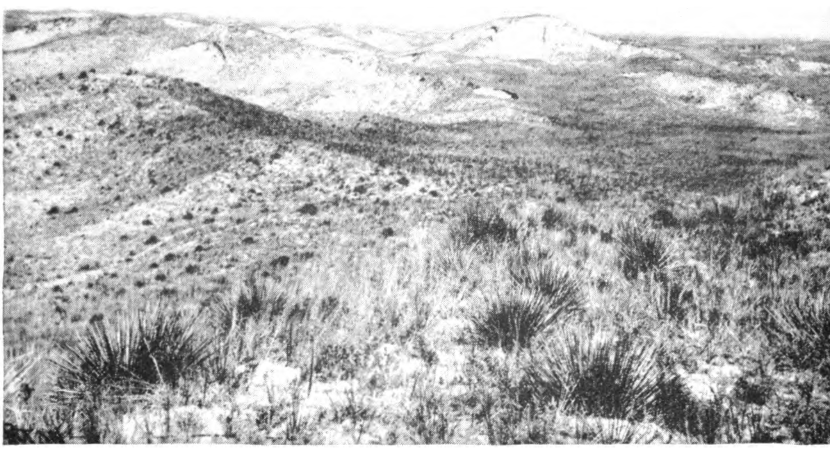

*Figure 122. Typical sand hills in the extensive sand belt region of central Nebraska.*

*b. Distribution.* In the United States, characteristic areas occur in western Kansas and Nebraska (fig. 122). Broad sandy deserts are widespread in southwestern North America, North Africa, southern Asia and Australia (fig. 123).

*c. Military Aspects.*

(1) *Movement.* Swampy, undrained depressions and slopes of loose sand hinder movement, but generally do not stop tracked vehicles. Ground is firmest when moist.

(2) *Observation; concealment and cover.* Some concealment and cover are afforded by sand dunes depending on their size. Observation is variable.

(3) *Water supply.* Water supply is generally limited. The small amount of ground water available at shallow depths in dunes is an important source of fresh water in desert areas. This

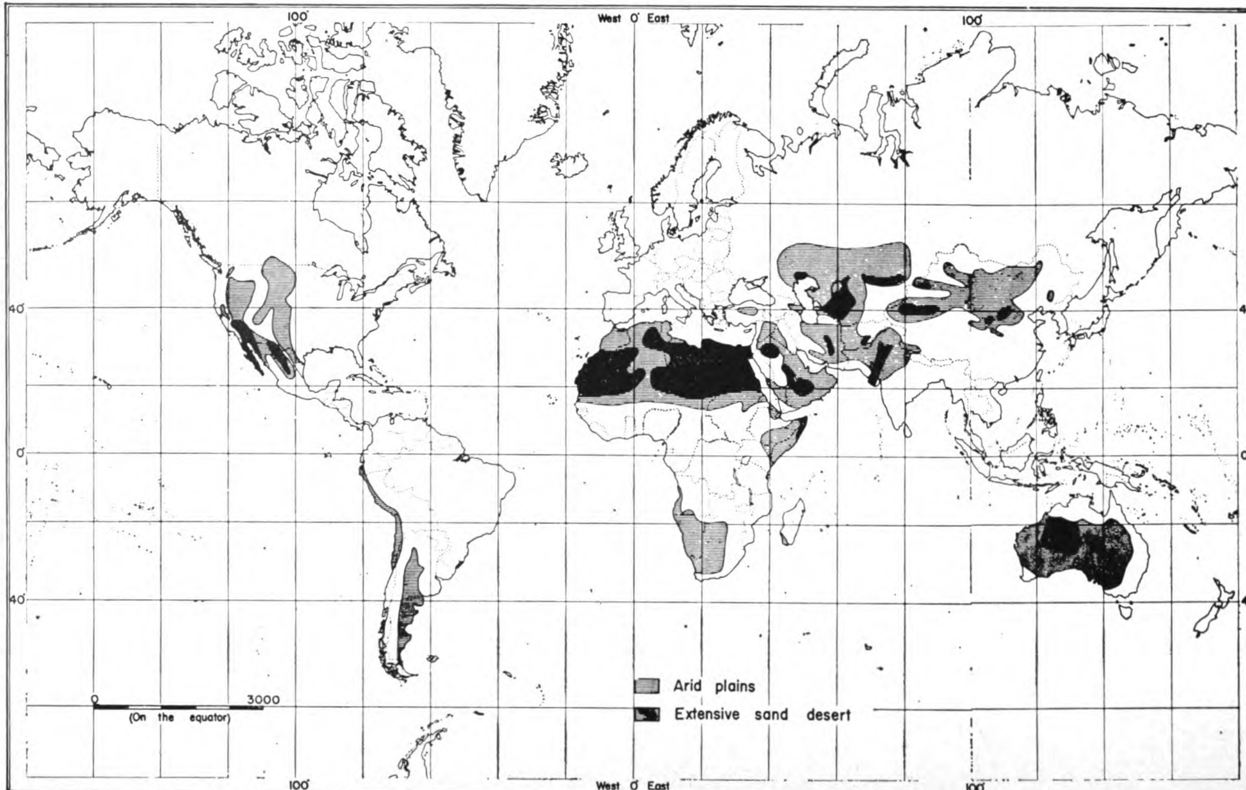


Figure 123. Arid plains of the world.

water originates from rain which sinks rapidly into the porous sand.

(4) *Construction materials.* Sand is generally the only material available for construction purposes.

(5) *Construction problems.* Sand-dune areas contain suitable sites for airfields. They are easily graded, but the loose sand must be stabilized. The soil is a good foundation if confined. Emergency airfields and roads are easily constructed with portable surface mats.

## 77. Loess Plains and Plateaus

*a. Description.* Windblown particles smaller than sand, mostly silt size (loess), have been deposited over broad tracts, generally along the margins of glacial plains and major streams flowing from formerly glaciated regions. The loess covers the underlying topography, tending to smooth out irregularities and produce a gently sloping surface. However, the peculiar ability of loess to stand in vertical walls produces very steep to precipitous escarpments along gullies, stream valleys, and artificial cuts (fig. 62).

*b. Distribution.* Characteristic loess topography and ground conditions in North America exist in parts of Missouri, Illinois, Iowa, Kansas, and Nebraska and extend south along the Mississippi Valley. A zone of loess extends across southern Europe; it is broadest in southern Russia. The greatest extent of loess plains and plateaus in the world is in China, between the North China Plain and Tibet. Other areas occur in North Africa and in the valley of the La Platta River of South America.

*c. Military Aspects.*

(1) *Movement.* In wet weather, ground conditions are very poor and movement may be stopped. In dry weather, movement conditions are good except for the escarpments and ravines.

(2) *Observation; concealment and cover.* Where vegetation is sparse, observation is generally good. Escarpments and ravines provide local concealment and cover.

(3) *Water supply.* Water supply is generally poor in loess. Small amounts of ground water may be secured by sinking shallow wells, but the yields are apt to fluctuate seasonally.

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(4) *Construction materials.* Little material is available except from underlying deposits, where exposed.

(5) *Construction problems.* Many good airfield sites and road alinements are available. Foundations need stabilization; in cold climates the loess may heave. Cuts in loess are unstable. In dry climates, thick loess deposits are well suited for underground installations because they are easily excavated.

## 78. Volcanic Plains and Plateaus

*a. Description.* Many areas have been buried by volcanic material to form extensive plains and plateaus. Ash and coarser material ejected from volcanoes spread over land surfaces, completely burying the old topography and producing an area of low relief. Lava flows from volcanic vents or fissures may also flood areas and form plains and plateaus. The surface of volcanic plains is generally featureless but in places is rough with small-scale irregularities formed by uneven deposition (fig. 124). Lava terrain is commonly highly dissected by steep-walled valleys which form isolated plains or plateaus (*c* on fig. 107 and fig. 113).

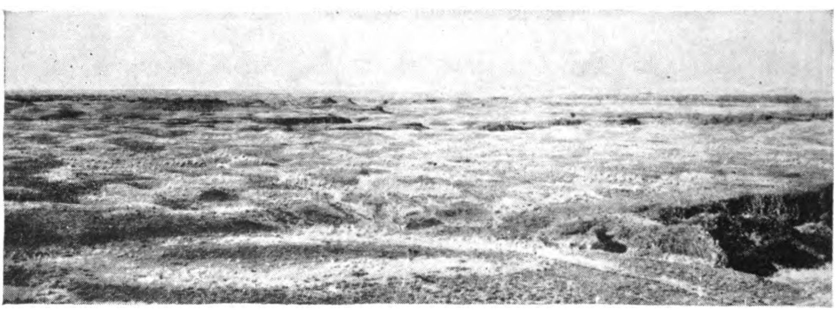

*Figure 124. Volcanic plain with rough surface (scablands). Near Grand Coulee Dam, Washington.*

*b. Distribution.* The Columbia River lava plateaus in the state of Washington are a typical example. Other large volcanic plains and plateaus are found in Mexico, Central America, Brazil, Iceland, East Africa, and India (fig. 125).

*c. Military Aspects.*

(1) *Movement.* Ravines, dissected margins, and marginal scarps are obstructions to movement. The rough surface may be

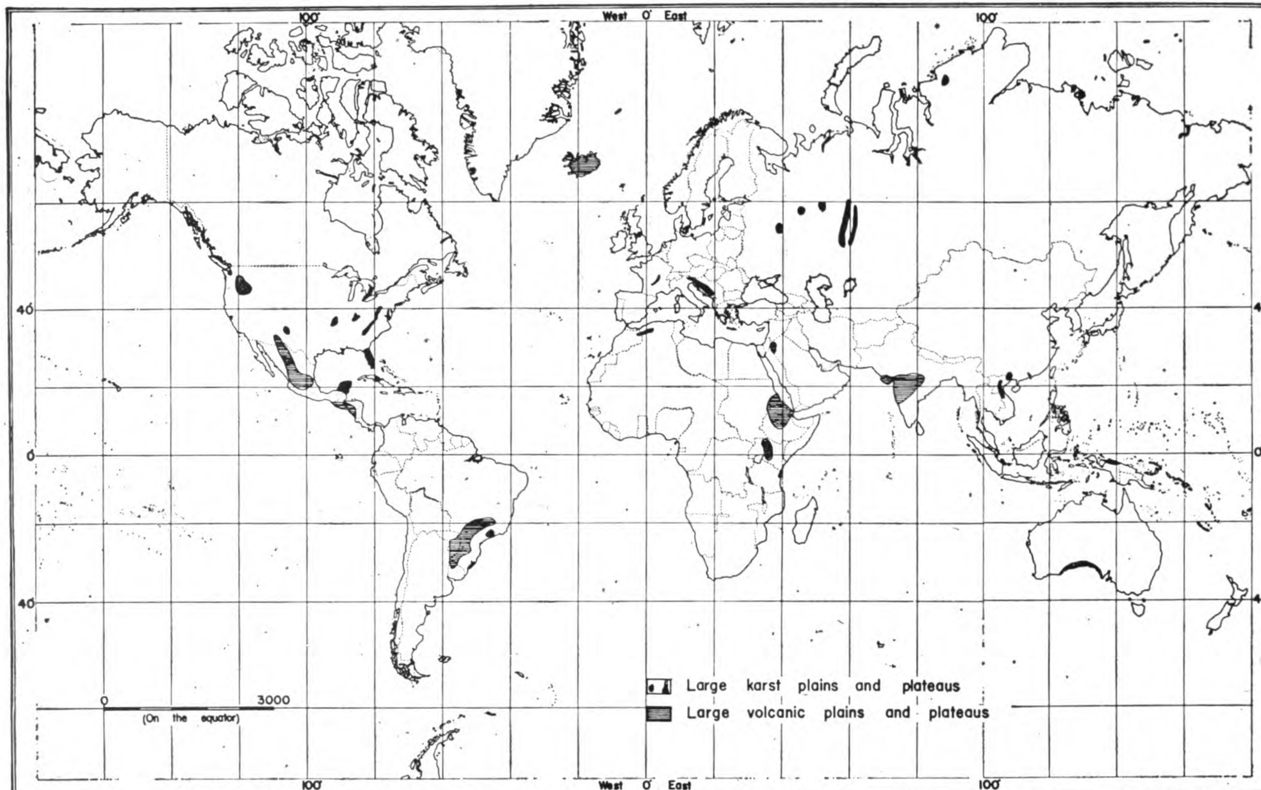


*Figure 125. Distribution of large volcanic and karst plains and plateaus.*

a hindrance. Soils on volcanic materials are commonly well drained and suitable for cross-country movement most or all of the year.

(2) *Observation; concealment and cover.* Observation is generally good. Cover is poor on the surface of the plains and plateaus but can be obtained at the erosion scarps.

(3) *Water supply.* Water is difficult to obtain. Streams are few. Some ground water is available but the distribution is erratic and careful prospecting is necessary.

(4) *Construction materials.* Hard trap rock is abundant and is easily quarried because of the close jointing. This rock makes good surfacing material and building stone. Sand and gravel are generally scarce.

(5) *Construction problems.* Many good airfield sites can be located. The topography and foundations are good for roads and airfields. Grading commonly requires excavation of hard rock.

## 79. Karst Plains and Plateaus

*a. Description.* A distinctive type of erosional plain or plateau is developed on limestone. A pitted or pinnacled surface is formed by the solution of the limestone, giving rise to karst topography. The origin of karsts plains and the resultant features are described in paragraph 31.

*b. Distribution.* Karst topography is well developed in the Ozarks of southern Missouri and in southern Indiana and western Kentucky. Karst also occurs in other parts of eastern United States, in the Caribbean area, Europe, and in scattered small areas elsewhere in the world (fig. 125).

*c. Military Aspects.*

(1) *Movement.* Movement can be fairly easy by avoiding sinkholes, which are likely to have swamps and ponds, and, in places, steep slopes. The clayey residual soil on the limestone may prove a hindrance in wet weather.

(2) *Observation; concealment and cover.* Observation is restricted by vegetation. The sinkholes provide some concealment and cover.

(3) *Water supply.* The supply of surface water is relatively small. Large springs, which are common in karst areas, are

the best source. Wells can yield large supplies if correctly located, but careful prospecting is required.

(4) *Construction materials.* Limestone, good for building stone and crushed rock, is abundant. Sand and gravel are generally lacking.

(5) *Construction problems.* In places, fair airfield sites can be found. Grading usually will require excavation of hard rock. Excavation is made difficult by the irregular rock surface of deep clay-filled pits and high pinnacles of rock beneath the residual soil. The possibility of foundation subsidence should be considered.

## 80. Modifications in Plains and Plateaus in Arid Regions

*a. Description.*

(1) Plains and plateaus in arid regions are largely treeless, flat areas. Any trees that are present are usually along water courses (fig. 190). Most streams are seasonal and many

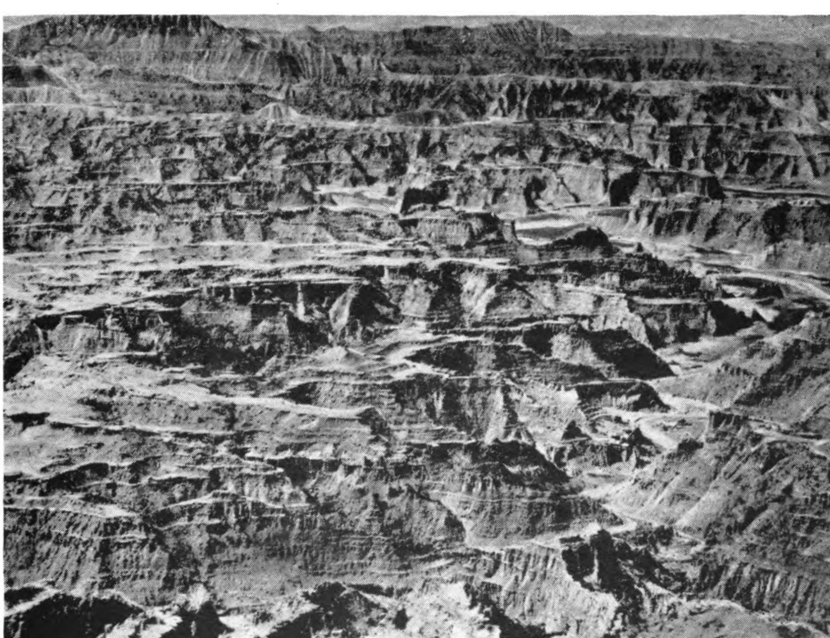

*Figure 126. Big Badlands. South Dakota.*

stream courses are dry for years. The larger streams in deserts commonly drain into interior basins and may end in saline lakes. Lakes are commonly playas (fig. 95) that dry up between rains.

(2) Rapid erosion in soft bedrock may develop an extremely rough topography consisting of numerous short ravines and sharp divides, called *badlands* (fig. 126).

(3) Sand dunes are characteristic of some deserts, but are less common and cover smaller areas than is generally realized. For instance only a part of the Sahara is dune-covered. Dune-less areas commonly have thin stony soils in which the finer sand and soil have been blown away. A layer of pebbles, called a desert pavement, has been left at the surface.

(4) Broad sloping alluvial fans are common on the plains near the foot of bordering mountains (fig. 127).

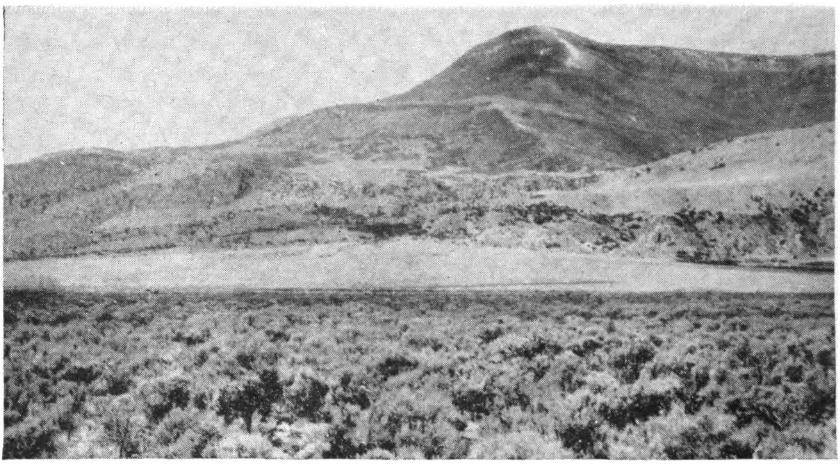

*Figure 127. Arid plain with alluvial fan at foot of mountains. Central Utah.*

*b. Distribution.* Typical arid plains and plateaus are in the south-western United States, in the interiors of Asia, Australia, and the Argentine, in North Africa, and in the Middle East. The world distribution of arid regions is shown on figure 123, excluding the arctic and antarctic regions where unique conditions prevail.

*c. Military Aspects.*

(1) *Movement.* Generally firm ground and lack of vegetation make for great mobility. This was demonstrated by the

Libyan strategy of both Rommel and Montgomery in World War II. Locally badlands or marshes provide obstacles to movement.

(2) *Observation; concealment and cover.* Arid plains allow miles of unobstructed observation. Cover is lacking except at the banks of dry washes and in dune areas.

(3) *Water supply.* Water is difficult or impossible to obtain in the quantities required by a motorized army. Much of it is highly mineralized.

(4) *Construction materials.* Sand and gravel are abundant and easy to obtain because of the absence of fine soil cover. In places, hard rock can be quarried. Termite mounds are a material that can be used for road surfacing.

(5) *Construction problems.* Arid plains contain many ideal airfield sites. Alluvial fans with gentle slopes and rapidly draining ground are particularly suitable. In most parts of the arid plains, including areas of desert pavement (*a* above), the ground needs little or no preparation for emergency landings and vehicle movements. Palliatives are necessary to reduce dustiness.

## 81. Modifications in Plains and Plateaus in Humid, Tropical Regions

*a. Description.*

(1) In contrast to those in arid regions, plains and plateaus in humid regions have many streams, deep soils, and dense vegetative cover. In populous areas the wild growth has been supplanted by gardens and plantations. Rice paddies, periodically artificially flooded, are common among the cultivated fields of the Orient.

(2) Low coasts are generally muddy and swampy and thickly forested with mangrove and other water-loving trees. In cultivated regions in the Orient the low coasts may be bordered by fish ponds, salt pans, and reclaimed land planted with rice.

(3) Coral reefs commonly fringe the coasts except at the mouths of rivers where the water is muddied by the streams. In the clear water, offshore barrier reefs parallel the coasts and surround the islands (fig. 128).

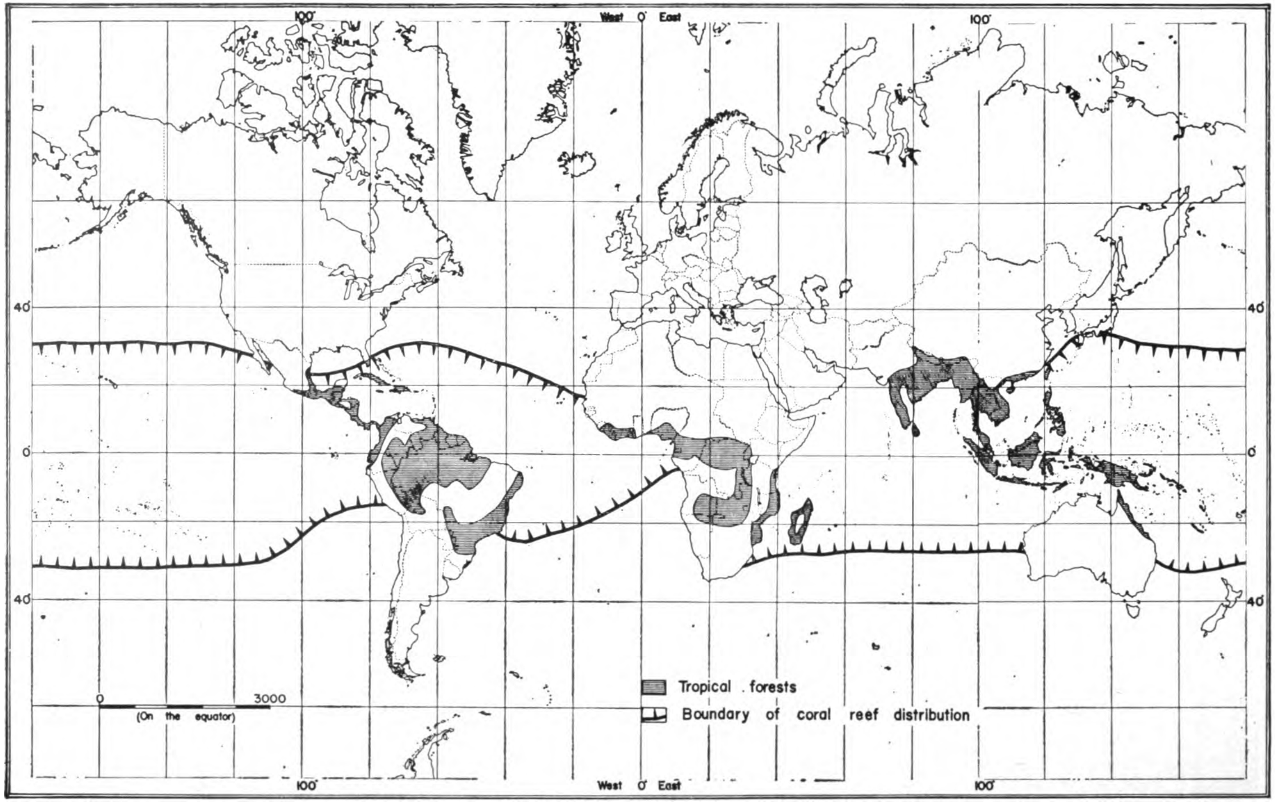


*Figure 128. World-wide distribution of tropical forests and coral growth.*

*b. Distribution.* The valley of the Amazon River is a typical jungle-covered plain. Central Luzon is another example. Figures 191, 192, 208 show coastal plains covered by tropical vegetation in Ponape and northern New Guinea. Figure 128 shows the world-wide distribution of areas with dense tropical forest (jungle) and of tropical seas in which coral reefs exist.

*c. Military Aspects.*

(1) *Movement.* The thick natural vegetation and some of the cultivated fields, particularly those planted in rice, seriously hinder movement. When rice paddies are flooded, the movement of motor vehicles may be restricted to roads; when the paddies are dry, their sunbaked floors can support any vehicle. The numerous low dikes remain as obstructions. The swampy and soft ground at the coasts is an obstacle, and the commonly clayey soils in better drained parts are difficult to cross in wet weather.

(2) *Observation; concealment and cover.* Observation is generally poor. In uncultivated regions it may be limited to a few feet.

(3) *Water supply.* Water is abundant but generally bacterially polluted. It is dangerous if untreated.

(4) *Construction materials.* The commonly thick soil mantle and deep weathering make firm rock difficult to obtain. Unique construction materials obtainable are laterite and coral limestone.

(5) *Construction problems.* Poor foundations and drainage problems are prevalent.

## 82. Modifications in Plains and Plateaus in Arctic and Subarctic Regions

*a. Description.*

(1) In arctic and subarctic regions, plains and plateaus are typically covered with tundra vegetation (moss, lichen, and grass, with low brush and stunted trees) and underlain by peaty soil. Toward the south, tundra is interspersed with forests.

(2) The plains and plateaus are poorly drained and lakes, marshes, swamps, and peat bogs are numerous. *Muskegs* are unstable tussocky bogs with deep accumulations of organic material common in northern regions (figs. 129 and 130).

(3) Under large portions of the arctic region the ground is permanently frozen and layers of clear ice occur within the soil (fig. 131). This frozen condition is called *permafrost.* The top of the permafrost lies a few inches to several feet below the surface, depending on mean annual temperature and the nature of the insulating vegetative and soil cover. The bottom of the permafrost lies at depths ranging from a few feet to over a thousand feet (fig. 132). A layer of ground overlying the permafrost is frozen in winter but thawed in summer. This is called the *active layer.* Dispersed throughout the active layer and the permafrost are nonfreezing soil layers or lenses called *taliks.* These nonfreezing layers carry water the year round and are the source of springs and wells.

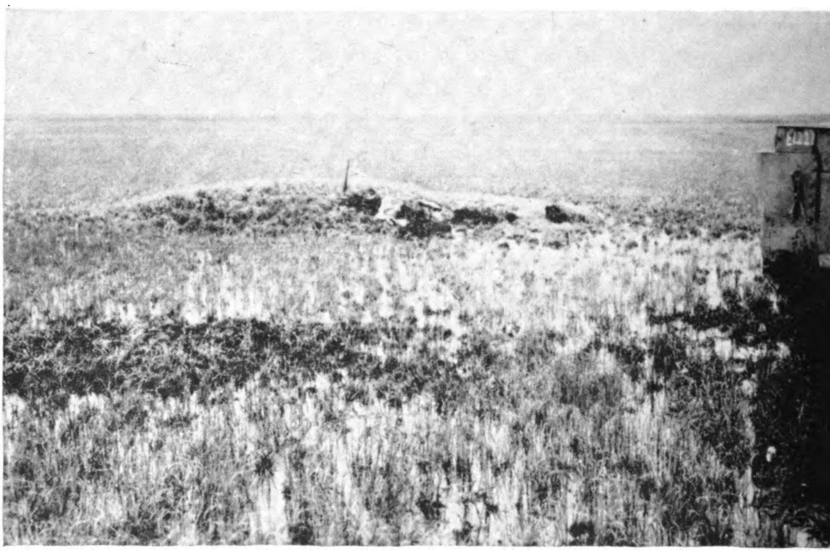

*Figure 129. Muskeg on Cape Simpson, Northern Alaska.*

(4) *Thermokarst* or *cave-in lakes* are typical of permafrost areas. They are formed by the settling, caving, and slumping of ground where silty, water-saturated permafrost has been thawed. Their shores are distinctively rounded or scalloped, where several sinks have united.

(5) Another common type of lake has a rectangular or polygonal shape. Such lakes are associated with a polygonal ground structure which is extensively developed in arctic regions (fig. 133). The ground polygons are defined by shallow

*Figure 130. Cross-section of a tussock.*

*Figure 131. Ice wedges in frozen sediments along a stream bank. Near Fairbanks, Alaska.*

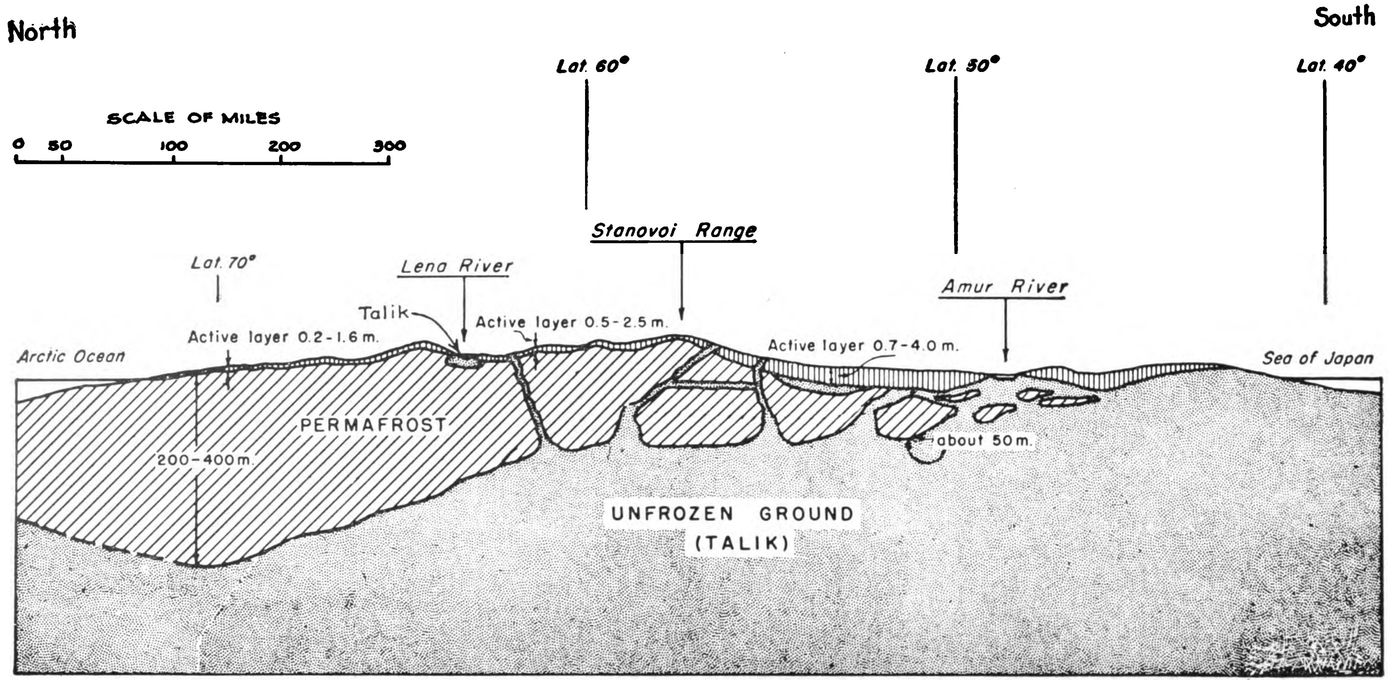


*Figure 132. Diagrammatic cross-section through Siberia.*

grooves or ridges in the ground, by heaved blocks of soil, or by textural differences in the soil. Wedges of ground ice are common between the polygons.

(6) Arctic and subarctic plains are generally of low relief except for frost and ice mounds of various sizes and shapes. *Pingos*

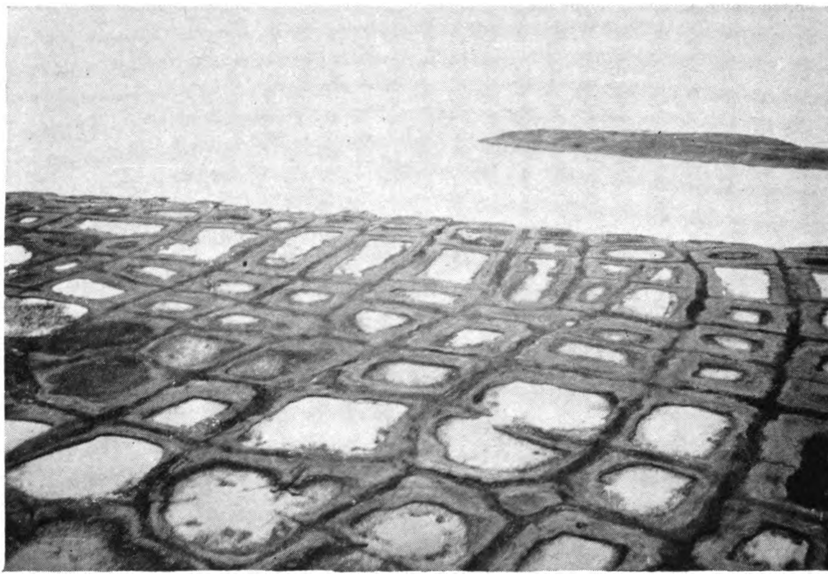

*Figure 133. Polygonal ground in northern Alaska. Lakes are approximately 20 feet by 20 feet.*

*Figure 134. Pingo on arctic coastal plain, approximately 60 feet long and 30 feet high. Near Point Barrow, Alaska.*

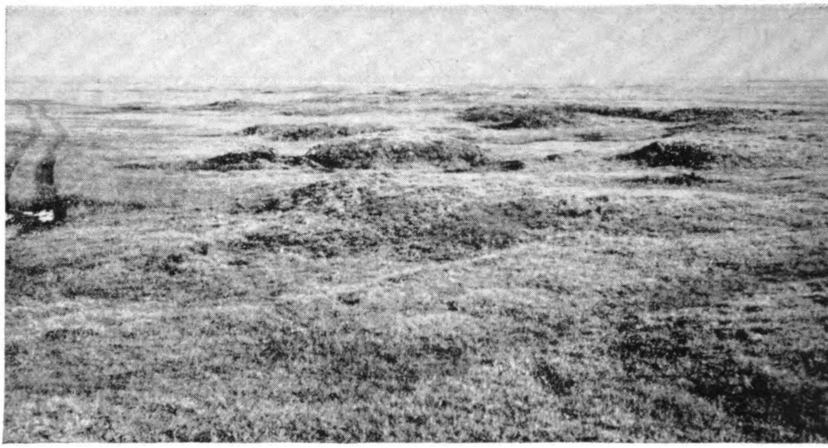

*Figure 135. Hammocky tundra. Near Point Barrow, Alaska.*

are isolated, symmetrically rounded mounds caused by swelling of ground over permafrost. They may attain a height of 300 feet and thus form the most prominent feature on an arctic plain (fig. 134).

(7) Smaller frost mounds and closely spaced vegetation hummocks 1 to 2 feet high extensively cover the plains (fig. 135).

(8) Large isolated mounds or sheets of ice also occur. They may be formed where water issues from the mouth of a perennial spring or they may be developed in winter wherever water finds an outlet from beneath the frozen active layer or from beneath the ice cover of streams, lakes, and marshes. The ice thus formed may accumulate to such a thickness that it lasts through the summer.

*b. Distribution.* The extent of tundra and of permafrost is shown on figure 136.

*c. Military Aspects.*

(1) Movement. During the summer the peaty ground is saturated with water. The spongy mass makes foot and vehicle movement difficult or impossible. Rivers and lakes are obstacles but in many cases offer the only transportation routes. In winter, ground is frozen hard but the polygonal and hummocky tundra makes overland movement difficult. In snow covered areas, movement is somewhat easier when the snow surface has crusted. In tundra areas, the absence

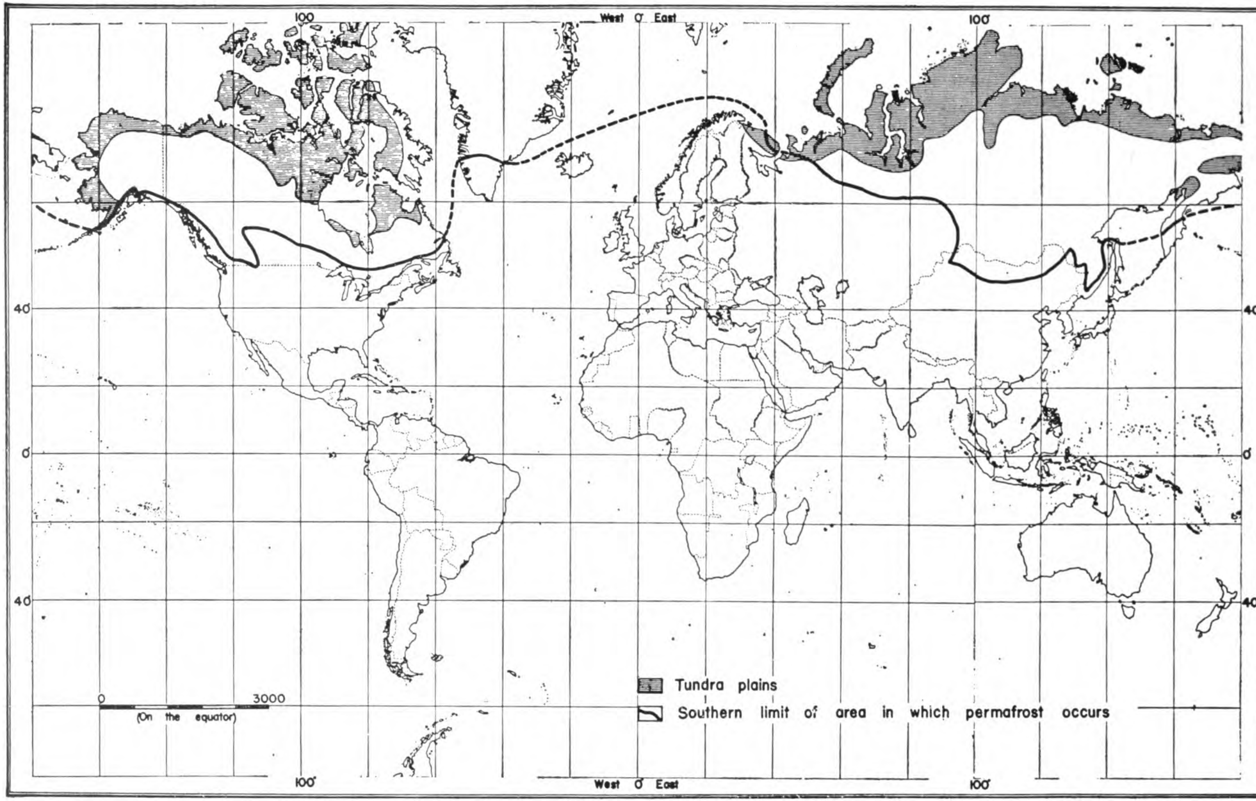


*Figure 136. Tundra plains of the world, and southern limit of permafrost region.*

of landmarks in the monotonous terrain increases the need for careful navigation.

(2) *Observation; concealment and cover.* Concealment and navigation is a serious problem in tundra areas. The lack of high vegetation makes concealment of vehicles almost impossible. The frozen ground prohibits digging in except in drifted snow. Observation is unlimited over flat surfaces.

(3) *Water supply.* Perennial supply is difficult to secure in arctic regions. In summer, surface water is abundant and shallow ground water may be present. Both are easily polluted. In winter, water can be obtained from below the ice in the larger lakes and rivers but it may be of bad quality because of high organic content. In some localities, as in the interior of Siberia, the water falls to low levels by late fall and freezes completely through even in the largest streams. Ground water above the permafrost, and springs fed by such water, are dependable only in summer, since some of this water freezes in winter and its subterranean channels and points of outlet may shift from summer to winter. Wells drilled into the nonfreezing water-bearing layers within or below permafrost are the best perennial source, but careful prospecting is necessary to locate the wells. Such aquifers are most common in floodplains near large rivers. An important problem of water supply is to prevent wells, intake pipes, and pipelines from freezing. One solution is to place heated structures over wells and pipelines, and to preheat the water. Water pipelines should be insulated. When buried, they are least likely to freeze if they are placed just above the permafrost.

(4) *Construction materials.* Many deposits of sand, gravel, and other unconsolidated materials are frozen solid and must be thawed by steam or other means. Surface rock that seems sound when frozen may prove weak and disintegrated when thawed.

(5) *Construction problems.* Permafrost presents many special engineering problems. If proper location and construction methods are not used, permafrost can cause failure of airfields, roads, and buildings. The main problems are heaving, settling in thawed ground, and poor drainage. The natural insulating vegetation and soil cover should be as little

disturbed as possible. A subgrade with a high crown and a thick, coarse base course are necessary in order to allow roads to drain and to minimize frost heave. Flooding by water from unfrozen subsurface layers may be caused by cuts, fills, and drainage ditches in connection with construction jobs. The highways of Alaska in winter are covered in many places by sheets of ice (locally called "glaciers" but more correctly known as *icings*), caused by water issuing from springs, ice covered streams, and swamps. These ice sheets create difficult road maintenance problems.

## Section IV. HILLS AND MOUNTAINS

### 83. Description

*a.* The terms *hill* and *mountain* are not sharply distinguished in either popular or technical usage. Whether some eminences are termed one or the other seems to be largely arbitrary. In the Rocky Mountains, elevations a few hundred feet high may be termed hills, whereas in the Middle West such elevations are termed mountains (fig. 137). Eminences higher than 1,500 or 2,000 feet are almost everywhere considered mountains.

*Figure 137. Rocky mountains, looking eastward near Pike's Peak, Colorado.*

*b.* In hills and mountains most of the slopes are greater than 4 degrees. Slopes may be vertical or even exceed the vertical in overhanging cliffs.

*c.* With respect to arrangement, mountains may form isolated summits, groups, ridges, or complex units termed *mountain ranges*. Two

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or more associated ranges may constitute a mountain system; for example, the Rocky Mountains. The terms *mountain chain* and *cordillera* are sometimes used to designate units of an even larger order of magnitude.

*d.* Hills and mountains of different localities vary widely in altitude, relief, area, and arrangement. The shape or form differs also. Some of the more important types of mountain forms, arising from rock structure, include fold mountains, fault-block mountains, dome mountains, and complex mountains, (par. 48). Other types are volcanic mountains (par. 42) and the distinctive forms produced by mountain glaciation (par. 29).

## 84. Distribution

The parts of the world where the surface is largely hills and mountains are shown in a generalized way on figure 114.

## 85. Military Aspects of Hills and Mountains

*a. Movement.*

(1) Hills and mountains are usually obstacles to movement. They generally favor the defense. History records many cases in which forces inferior in numbers and equipment have held off superior attackers in mountainous areas.

(2) Factors which are unfavorable to troop movements over mountains are the difficulty of movement, the lack of space for maneuvering, and the vulnerability of the lines of communications. If a mountain crossing is chosen, these unfavorable factors must be outweighed by important strategic considerations. Military records include many instances in which such obstacles have been successfully overcome. Among the better known are the battles on the Austro-Italian front in World War I, and the battles in Italy, New Guinea, and the Philippines in World War II. In North Africa and again in the approach to the Rhine through the Middle Rhine Highlands, surprise was effectively achieved by moving over hill and mountain terrain instead of through the adjacent corridors where the enemy was prepared.

(3) Valleys provide corridors through hilly and mountainous regions. Most of them are narrow defiles. In fold mountains, the valleys are generally oriented parallel to the moun-

tain trends and favor movement in that direction. In other types of mountains, the valleys are arranged radially or provide corridors across the mountain trend. Passes across divides include such features as water gaps, wind gaps, cols, and, rarely, calderas.

(4) Ground factors bear directly on rapidity and safety of movement on mountain slopes. Although the opposite sides of a peak or ridge may look rather alike on a topographic map, actually they may differ in features which make movement much easier on the dip slope than on the scarp side. The sides may differ with respect to the hazards of rockfalls, avalanches, and snowslides; the firmness and abundance of holds that must be used in climbing; the amount of snow and ice in crevices; dryness of rock surfaces; and the kind and amount of cover for troops. Crestline movements along ridges may be much more advantageous in certain directions.

(5) Alternative routes are commonly available in volcanic mountains over slopes of hard lava rock or loose ash and cinders. Although loose ash and cinders are usually difficult to cross, they have the advantage of allowing troops to dig in rapidly. This was the case at Iwo Jima. In other types of mountains, the choice may lie between operating on shaly limestone, which is unreliable because it is brittle and crumbly, or on gneiss, a firm granite-like rock that gives excellent footing. Some rocks, like argillaceous limestone, give good footing when dry but are treacherous when wet, since they become soft or slick. Others, like granite, are little affected by water.

*b. Observation; Concealment and Cover.* The rugged topography of hills and mountains provides abundant opportunity for concealment and cover. Above the timber line, movement across most slopes or crests is exposed to view from many directions. Observation is variable.

*c. Water Supply.* Precipitation is high in mountains. In the lower slopes, numerous streams or springs can provide small to moderate supplies of water. In the higher slopes, dependable sources are few and small. When vegetation is sparse the runoff is rapid and high, and the flow of streams in hills and mountains fluctuates considerably. Where vegetation is abundant, the runoff may be retarded so that water from small perennial streams can be used for troop supply. A large, permanent water supply generally can be obtained only from lakes or reservoirs. In crystalline rocks, large-yielding wells can be

drilled, but the factors controlling the presence of ground-water may be so variable, that the chance for finding adequate supplies may be small (par. 171). The alluvial bottoms of the larger streams provide good locations for wells.

*d. Construction Materials.* Many types of hard rocks suitable for construction are easily obtained in hills and mountains. Geologic maps are the best source of this information. Sand is scarce, but gravel is obtainable in the lower stretches of streams, where they approach the foot of mountains or flow through hills.

*e. Construction Problems.*

(1) Locations for runways are few in hills or mountains. Ever-present problems are excavation in hard rock, obstructed or limited approaches, poor accessibility, disturbing air currents, and the hazards of bordering peaks and escarpments.

(2) Highways, railroads, and tunnels are highly vulnerable in hills and mountains. Geologic data are useful in indicating rock conditions where bombing or artillery fire can initiate slides and block lines of communication. Geologic data can also be of use in selecting sites suitable for gun emplacements and other fortifications, in estimating the probable effect of fire on rock fragmentation, and in determining the possibility of ricocheting of projectiles.

(3) The digging of foxholes and other temporary fortifications is generally difficult in mountains, because if any soil exists it is thin or stony and the bedrock is commonly hard. In certain mountains, like the Blue Ridge, some areas may have soil several feet deep. Geologic study will assist in the selection of slopes on which troops can most readily dig in. Where bedrock is at or near the surface, a geologic map will usually indicate areas underlain with softer rock, like shale and tuff, in which excavations may be possible with hand tools. Where harder materials are involved, geological data can aid in the estimation of the amount of blasting required and the selection of the proper excavating equipment.

# CHAPTER 5

# FOUNDATIONS AND EXCAVATIONS

## Section I. GEOLOGIC EVALUATION OF FOUNDATION SITES

### 86. General

The geologic factors to be considered in evaluating natural foundations for any military structure are discussed in this section. The climate, the type of structure to be erected, and the phase of the military operation determine which of the factors must be considered. The phase of the military operation is probably the most important to the engineer; within the limits of broad strategic planning there may be a wide choice of sites, but in tactical operations there may be a limited number, or no choice at all.

### 87. Bearing Capacity of the Soil or Rock

*a. Geologic Considerations.*

(1) In the field of operations, the engineer rarely has to construct massive structures. The weight which the engineer puts upon the natural foundation is very small and, therefore, can be supported by most rocks and soils.

(2) On unconsolidated material (soil), except in permafrost areas, the usual type of military construction will present no problem unless the soil is peat, soft clay, soft silt, or fine sand free to move (as in sand dunes), or when there is unusual shattering or solution cavities in the underlying rock mass. (The bearing strength of unconsolidated material in permafrost regions is discussed in paragraph 94*a*.)

(3) On consolidated material (rock), factors such as joints, faults, the amount and direction of dip, and the degree of variation in thinly bedded formations all influence the pressure which can be safely applied.

*b. Construction Measures.*

(1) *General.*

(*a*) Engineers usually adopt one or a combination of several methods of transmitting loads to natural foundations or overcoming the instability of natural foundations (fig. 138). Spread footings or floating rafts which rest directly on the unconsolidated material may be constructed, or piles may be sunk or driven into the unconsolidated material. The latter are founded on material capable of supporting the load and designed as columns. In the absence of such material, reliance is placed upon skin friction to provide bearing.

*Figure 138. A four-foot foundation of rock used on a Virginia soil road to overcome the instability of the natural foundation.*

(*b*) When firm rock is covered with material which has a low bearing capacity, the correct approach to the foundation problem may be to remove the cover entirely. For example, in Normandy, where loam overlies limestone, certain roads became impassable during the winter season. In only 2 days, the loam cover, approximately 6 feet deep, was bulldozed off in lanes, making movement possible on the exposed top of the limestone.

(2) *Buildings.* Building failures are generally related to failure of the foundation beds to carry the loads put upon them. The normal military building load, however, rarely exceeds

the bearing strength of consolidated material. If compression tests have to be made, they should be made with specimens oriented to correspond with the attitude of the rocks at the building site, and loaded to correspond to the direction of thrust of the building. The bearing strength of certain sedimentary rocks when tested parallel to the stratification may be as much as 50 percent less than when tested at right angles to the stratification.

(3) *Bridges.*

(*a*) Foundations and approaches for bridges need particularly careful investigation. Since bridges are usually constructed in valleys, the river-laid deposits are often of poor bearing strength, extending to considerable depths below the ground surface. Since the valley's deposits of sand, silt, clay, gravel, and peat will not occur in any prescribed order, they should be studied before any large bridging program is undertaken. Either a study should be made of reports on previous work done at the bridge site or a

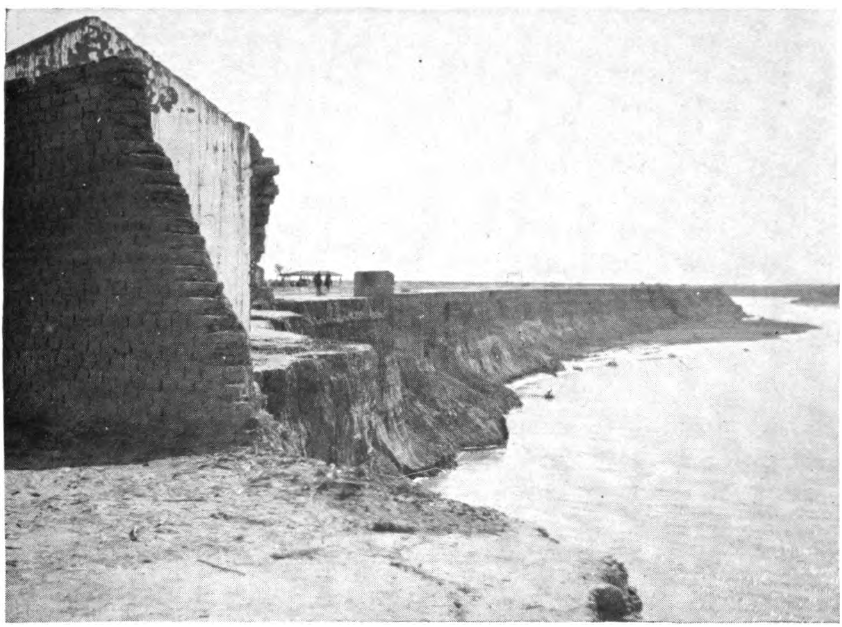

*Figure 139. Building, constructed in bendway, destroyed by stream scour along concave bank.*

large series of exploratory boreholes along and adjacent to the line of the bridge should be dug.

(*b*) A bridge should be sited at some place along the straight stretch of a stream. If placed on the bendway, the approach and footing on the concave bank of the stream will be subjected to intensive scour. In time, scour will cause the bearing strength of the foundation material to become greatly impaired or dissipated (fig. 139).

## 88. Solidity and Thickness of Strata in Interbedded Series

*a. Geologic Considerations.*

(1) The surface layer in a stratified series of rocks may be sufficiently strong in itself to carry the load transmitted to it, but another stratum below it may be plastic, permitting movement or settling of both the overlying stratum and the structure resting upon it. If incompressible rocks are interbedded with plastic clays and if the strata are horizontal, the interbedded clay would be largely prevented from flowing laterally since it would be imprisoned on all sides. If the beds were inclined, however, or the structure subjected to horizontal pressure, such as applied by an impounding dam, the clay might be squeezed out and would require special consideration.

(2) Interbedding is particularly prevalent in river deposits and, owing to the changing history of a river, is likely to show much variation in horizontal distribution and in a vertical section (fig. 140). Peat may form the surface but, a few feet down, pass into clay, which is itself underlain by sand and gravel. If a structure is founded on either the peat or the clay, the clay may be quite inadequate to take its thrust. If founded on the gravel, by use of piles, the foundation will be stable. In another case, however, sand might overlie a much weaker layer such as peat or soft clay. Light structures on this sand would be satisfactory, whereas heavy constructions might transmit sufficient thrust through the upper layer to deform the weaker substratum, leading to failure. Further complication arises from the fact that any particular bed of material encountered in a section at some particular point cannot be expected to continue across the

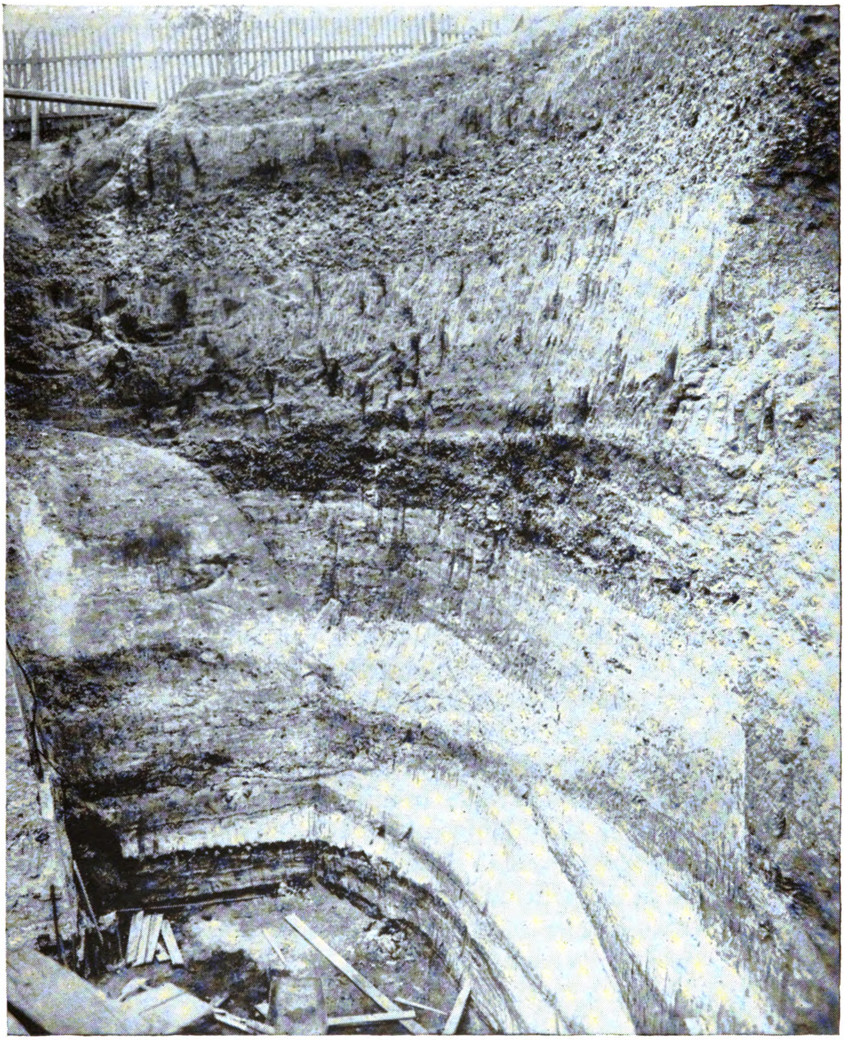

*Figure 140. Vertical section showing interbedding in alluvial deposits. Washington, D. C.*

valley without change in level or thickness. All beds must be regarded as lenses, likely to thin out or disappear laterally.

*b. Construction Measures.*

(1) In incompressible rocks interbedded with plastic material, the safety figure for loading stresses should be that of the

weakest member of the interbedded series. An exception is made to this rule in vertical strata where the incompressible rocks could be used to support the weight of the structure.

(2) In river alluvium, it may be necessary to take a greater number of exploratory boreholes along the line of the structure to determine the depth of a satisfactory foundation material. Construction procedures thereafter would follow the general practices outline for unconsolidated material in paragraph 87*b*(1).

## 89. Inclination of Stratified Beds

*a. Geologic Considerations.* The greatest hazard in inclined beds is their tendency to creep or slide. The beds have a natural tendency to move downward along the inclined bedding planes. The movement is assisted by the lubricating action of water. In the study of a foundation site where sliding might occur, the possibility that ground water will be present at some time of the year must be considered, even if the rocks appear to be dry at the time of initial examination.

*b. Construction Measures.*

(1) Wherever practical, construction on inclined strata should be avoided. Since this is not always possible, the following preventive or control measures may reduce slippage at the construction site.

(*a*) Divert surface water from an area where potential movement is judged present.

(*b*) Grout joints and bedding planes beneath and upslope from the structure. This measure has been found effective both in increasing the strength of the natural foundation and in excluding water.

(2) One factor influencing the safe angle of repose of material in cuttings is the relationship of the bedding planes, joints, and faults to the direction of the cuttings. Paragraph 97 covers this aspect of selection of foundation sites in detail.

## 90. Fault and Earthquake Zones

*a. Geologic Considerations.*

(1) *Fault zones.* Faulting is a common phenomenon in many regions. Even in non-earthquake areas, this intermittent movement occurs. Faulting causes the engineer trouble

because the rock formations along the fault line are usually disturbed. When the rock is so greatly shattered as to produce a zone containing fine-grained impervious clay-like material (gouge), the bearing capacity of the foundation is impaired. In other instances, shattering may increase the permeability of the rock and thus permit underground water under hydrostatic head to produce a line of springs along the fault zone. Although some solutions passing through these channelways may carry sufficient mineralizers to cement the shattered rock, making it stronger than before, the percolating waters may produce an opposite effect. Rock may be changed to rotten, swelling, or squeezing ground within the fault zone and on either side.

(2) *Earthquake zones.* Allowance for earthquakes is not a precaution which the engineer need consider except in parts of the world which have well-known shock zones (fig. 78). Nearly all earthquakes on land originate as a small movement along a fault. The resulting vibrations set up in the rocks cause more or less damage, sometimes for a distance of several miles from the fault line. In any unstable area there will often be perfectly well-known and well-mapped fault lines which are likely to be the focal areas of the centers of earthquakes in the future. These are the areas which should be given special consideration in the selection of a foundation site.

*b. Construction Measures.*

(1) Areas where bedrock is cut by faults should be avoided as sites for foundations or any major structure. This is particularly true for underground installations.

(2) In earthquake zones, it is probably impossible to construct any military structure which cannot be damaged, but certain precautions can be observed where earthquakes are known to occur.

(*a*) *Roads.* If earthquake belts have to be crossed, it is better to aline the road so that it crosses sharply across the fault rather than to allow it to run along or near the fault line for any great distance. It is better to choose a route which avoids the use of bridges as much as possible or one where any such major constructional works will not lie close to possible future shock centers.

(*b*) *Buildings.* Damage by earthquakes can be minimized by proper location and construction materials. Buildings resting on bedrock and having an elastic framework are least likely to suffer severely, because solid rock has a very small amplitude of vibration. Buildings on alluvium (particularly if water-soaked) are commonly shaken more violently than those on bedrock, beoause the alluvium vibrates with a larger amplitude. Brick and masonry structures are especially susceptible to damage, since the shock is not transmitted through the structure with equal intensity and the bricks or stones are shaken apart.

## 91. Joints

*a. Geologic Considerations.* Instability in rock, stratified or unstratified, is quite often caused by closely spaced joints which traverse the mass. These joints are often slightly open fissures down which water has carried clay; they are, therefore, potential slide surfaces for landslips. It sometimes happens that these joints are so closely spaced that a situation is reached where the angle of slope is that for an incoherent material.

*b. Construction Measures.* Areas of jointing are to be avoided, if possible. The safe angle of the cut slope is discussed in paragraph 97.

## 92. Surface and Subsurface Drainage

*a. Geologic Considerations.*

(1) Foundations which may be thoroughly treacherous in the wet seasons may falsely appear to be sound during dry periods. This is particularly true in clay-covered upland plateau regions which may be transformed to a sticky plastic state in winter because of a slow rate of surface runoff.

(2) Clay also has a tendency to slide when it becomes water-soaked, the whole mass flowing like tar.

(3) In limestone or chalk districts, underground solution of the rock by circulating waters may produce large caverns. If the top of one of these caverns approaches too near the surface, the ground collapses into the cavity. This possibility justifies the exploration of conditions below the bearing surface of a natural foundation composed principally of water-soluble rocks.

*b. Construction Measures.*

(1) When a foundation or embankment is likely to be damaged by surface-water runoff, it may be protected by constructing a drainage ditch upslope from the site.

(2) Sites covered with water or saturated with water which cannot be drained to lower land by gravity, may be drained by rising pumps or well points (figs. 141 and 142). Trenches in some localities, for example, may be freed of water by draining the water into wells that end either in an unsaturated porous bed or in an aquifer whose water is not under sufficient head to rise to the bottom of the trenches (fig. 143). In such localities, the water that causes the trouble is a perched body, supported above the general water table of the region by some impervious or slightly pervious bed.

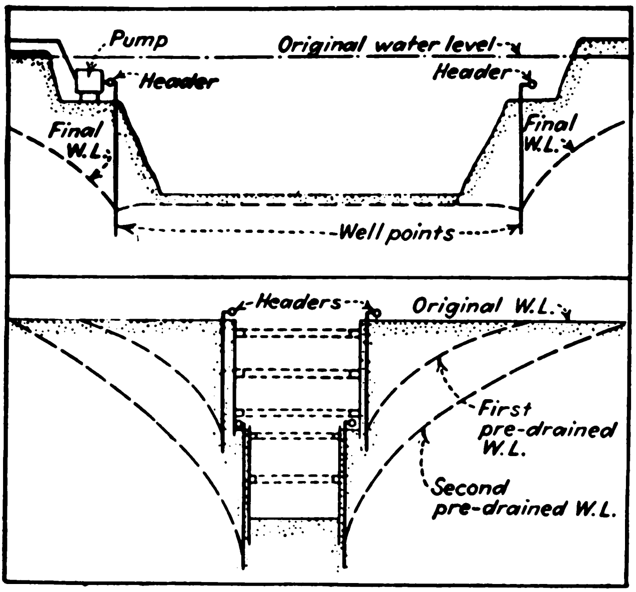


*Figure 141. Diagrams illustrating the use of well points for open and for trench excavations in water-bearing ground.*

(3) Areas underlain by soluble rocks where sinks may exist should be avoided if possible. If construction is necessary on such locations, reconnaissance is needed to avoid the worst solution conditions such as underground channels that

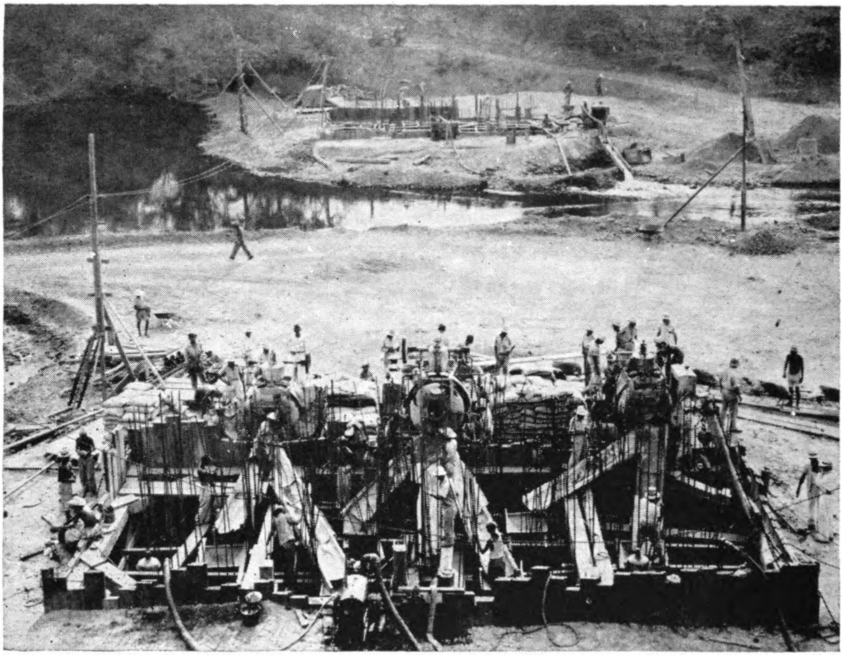

*Figure 142. Dewatering bridge-pier site by pumping. Rio Grande de San Miguel, El Salvador.*

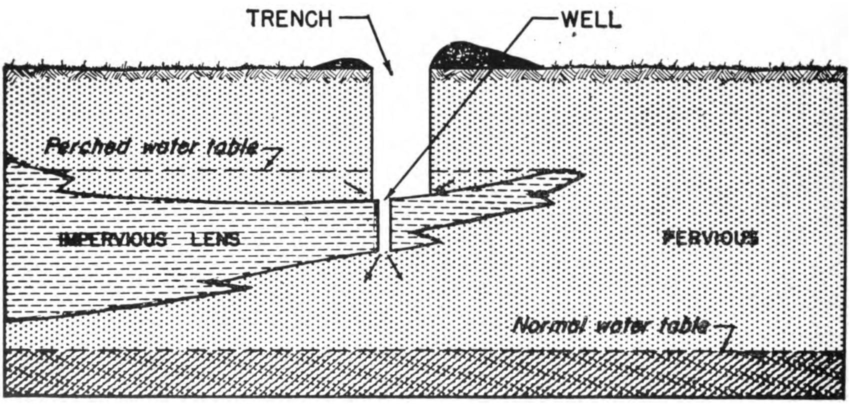


*Figure 143. Method of dewatering trench that intersects perched water table.*

may be identified by a line of springs, alined sinks, or disappearing streams. Aids to the protection of a structure located in soluble rocks include the construction of im-

pervious, lined ditches to prevent surface drainage from contributing to underground solution and diversion of subsurface channels. Where sinks develop under a structure, such as a runway, they are excavated and filled in with coarse material or, if leading to a channel, are converted to a roofed drain.

## 93. Frost Heave and Thaw

*a. Geologic Considerations.*

(1) *Frost heave.*

(*a*) In areas where severe and prolonged frosts are experienced in winter, serious damage may be caused in certain structures, particularly roads and airfields, by the freezing of water in the road itself or in its foundation.

(*b*) Water contained in pores of the soil, which are sufficiently large for capillary action to be negligible, will freeze at about 0° C. It has been proved that water held in fine capillaries solidifies only at much lower temperatures, frequently —20° C. and in extreme cases as low as —78° C. If, however, ice crystals have commenced to form in the large cavities, they will attract water from capillaries, which then freeze. The soil as a whole does not freeze, but numerous ice lenses grow within the soil. Each lens grows by abstracting capillary water from the surrounding soil and also, if the situation allows it, by drawing water from below the depth of freezing. The expansion of the ground caused by this development of ice causes uplift which is known as *frost heave.*

(*c*) Under suitable conditions, all types of soils can be subjected to frost heave, but the actual occurrence varies with the soil. Soil type, depth of frost, and position of the water table are all factors which prevent a prediction as to exactly where frost heave will occur, allowing only general indications of zones of relative probability. Sand, for example, has a high permeability, but is nevertheless not usually susceptible because the water table is likely to be well down and the capillary fringe is negligible. Plastic clay does not heave much because it has virtually no permeability and the water does not freeze in its

capillaries. On the other hand, fine-grained material with a low plasticity, such as silts, clayey silts, organic silts, and peats, combine sufficient permeability with a moderate capillary fringe to place them frequently in a heaving condition. Table V lists the potential frost action of the different soil types.

(2) *Damage in thawing.* The serious effects of thaw deterioration are most notable in roads and airfields. Damage is done during the freezing but it may pass unnoticed while the ground is hard. When the thaw sets in and works downward, whole lengths of road may be unserviceable. Buckling occurs under traffic, the surface is broken up, and vehicles are bogged down in what appears to be more like quicksand than a road. The reason for this road failure is apparent. Failure occurs only where ice growth has taken place in the foundation or construction materials. Soil, in order to be capable of bearing loads, must have its mineral particles in contact, and therefore its water content must not exceed a critical amount. If ice growth has occurred, drawing additional water from the exterior, it is likely that, on melting, the soil will drain itself. Drainage will take longer in silts and loams than in sand.

*b. Construction Measures.*

(1) The following rules should be followed as far as possible in selecting road sites in regions where severe and prolonged winter frosts are experienced; they are also applicable to most structural sites in temperate and subarctic regions.

(*a*) Avoid north-facing slopes (in the northern hemisphere), where frost penetration will be deepest.

(*b*) Choose sand, gravel, or solid rock as natural foundations.

(*c*) Avoid valley bottoms, where the water table will be near to the surface. In places where valley bottoms cannot be avoided, build up the road formation with sand, gravel, or rubble to a safe height.

(*d*) Avoid places where impermeable beds underlie the surface at shallow depth, where water will be held close to the road for some time after rain.

(*e*) Avoid obvious water seepages.

(*f*) Construct good drains to keep the water table well below road surface.

(2) In areas where damage might occur during thawing, traffic on roads should be avoided if possible and drainage should be continued to hold the water table well below the unstable layer. In a short time, the excess water will become drained and the surface firm, without extensive damage.

## 94. Permafrost

*a. Geologic Considerations.* Soils increase in strength with lowering of temperature. Those of low bearing capacity before freezing strengthen faster than the better types. Almost any type soil has sufficient bearing strength for the normal military structure as long as the foundation material remains in a permanently frozen condition. Since the bearing strength of the foundation is assured if footings are placed in the permafrost, the most difficult design and construction problems in permafrost areas are: heaving and icing due to freezing action in the active zone; and settlement due to thawing of the permafrost.

(1) *Effects of freezing.*

(*a*) The permafrost layer acts as an impervious plane which holds the ground water in the active layer. Frequently, the entire active zone is saturated. A water table is, therefore, always near the surface when winter surface freezing begins, thus making conditions ideal for the supply of extraneous water which leads to excessive ice growth or frost heave (par. 93) in the soil.

(*b*) Even more destructive effects are brought about by the fact that the downward freezing will proceed unevenly and the active zone is welded to the permafrost table in one place before another. Thus there is trapped, between two layers of frozen ground, an unfrozen belt charged with water which may have a considerable head behind it. As the hydrostatic pressure grows, the ground may bulge up to form a *frost blister.* The blister may burst and a mass of water or mud may seep out, freezing as it does so and building up an *ice mound* or spreading out as a sheet of ice. If the pressure of water is maintained, the mounds may grow many feet high or the sheets of ice may be extensive.

(2) *Effects of thawing.* Uneven settling during thawing causes great damage, especially to buildings (fig. 144). Often, the

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mere erection of a structure is sufficient to alter thermal conditions so that unequal settlement will take place. For example, the ground adjacent to the south-facing wall of a building receives both direct solar radiation and reflection from the wall, and therefore thaws earlier, quicker, and deeper than soil in the shaded, north side of the building. Unequal settlement usually results.

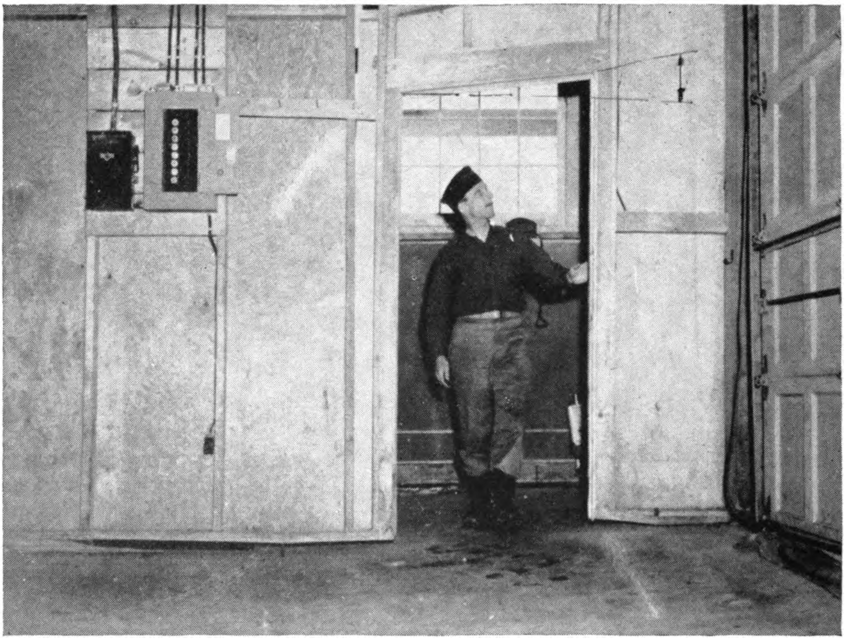

*Figure 144. Garage at Northway Airfield, showing settling due to improper construction on permafrost.*

*b. Construction Measures.* The special foundation problems encountered in arctic and subarctic climates are covered in Strategical Engineering Study No. 62. "Permafrost or Permanently Frozen Ground and Related Engineering Problems," OCE, March 1943. In general, buildings should be placed on piles which penetrate the permafrost or on thick gravel mats. Roads should have a high crown and a thick base course. Natural vegetation and soil cover should be disturbed as little as possible.

## Section II. OPEN EXCAVATIONS

### 95. General

In open excavation work, it is desirable to know the nature of the materials that have to be handled, their relative structural arrangement, their behavior when removed from their existing position, the possibility of the presence of water during excavation, and the possible effect of the excavation on adjacent ground and structure. These factors must be carefully considered before the excavation begins, to avoid trouble later.

### 96. Materials to be Excavated

*a.* As a general rule in excavation work, the engineer is not interested in the type of rock, in a geologic sense, that has to be excavated, but only in its character in relation to excavation methods. Such a classification has been established by the American Society of Civil Engineers through its Joint Committee on Substructure Engineering. This classification defines the materials of the earth's crust with respect to their workability; "Earth is material which can be removed and handled economically with pick and shovel or by hand, or which can be loosened and removed with a power shovel. Soft rock can be removed by air-

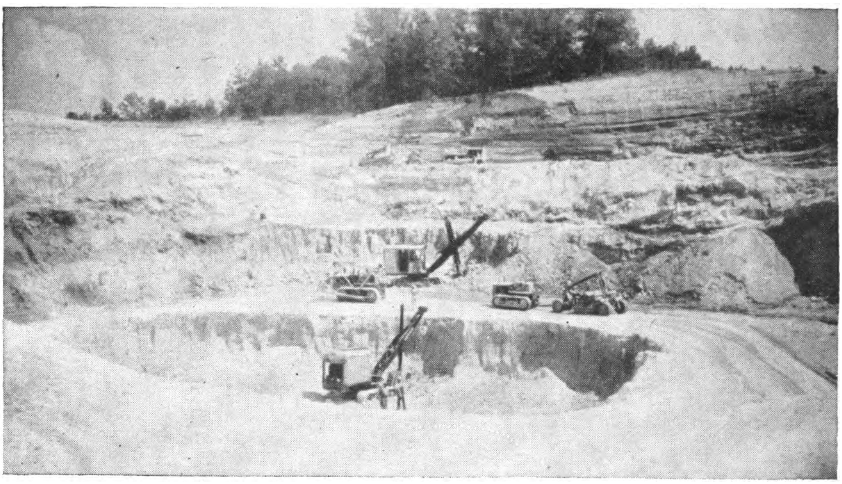

*Figure 145. An example of earth as defined by American Society of Civil Engineers. Eufaula, Alabama.*

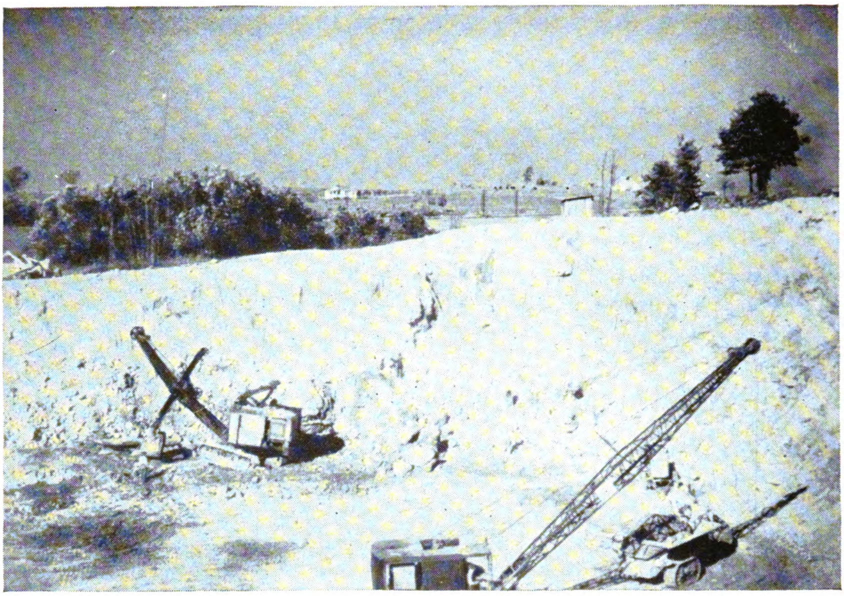

*Figure 146. An example of soft rock as defined by American Society of Civil Engineers. An air-operated hammer is loosening rock ahead of the shovels. New Market, Tennessee.*

operated hammers, but cannot be handled economically by pick. Hard rock requires drilling and blasting for its economical removal." This classification is advisedly used in contracts for civil engineering projects where legal disputes very often arise over payment for excavating material that has a controversial classification, but it is not readily adaptable to this manual.

*b*. For the purposes of this section and the following chapter on "Construction Materials," earth materials are classified as unconsolidated (soil) and consolidated (rock). From the standpoint of workability, unconsolidated material constitutes the "earth" of the A.S.C.E. classification system (fig. 145); consolidated material includes both the "soft rock" (fig. 146) and "hard rock" (fig. 147). Consolidated material, therefore, is that which requires some medium of loosening at the excavation site (bulldozer, rooter, air-operated hammer, or blasting) before it can be handled.

*Figure 147. An example of hard rock as defined by American Society of Civil Engineers. Blasting is used to loosen the rock. Cartago, Costa Rica.*

## 97. Safe Angle of Repose of Material in Side Slopes

In open excavations, geology has been utilized in the determination of the safe angle of repose of the material in the side slopes or cut banks. On the basis of certain geologic considerations and practical experience, tables of angles of repose for materials of various kinds have been established. These tables are useful, but complete reliance on them is inadvisable since the geologic factors involved in their determination are extremely variable. The critical geologic factors involved are the nature of the material being excavated, whether consolidated or unconsolidated, whether homogeneous or non-homo-

geneous; the relationship of structures, such as bedding planes, joints, and faults to the direction of the cut bank; and the disposition of surface and ground water.

*a. Nature of the Material Being Excavated.*

(1) The sides of excavations have a wide range in the safe slope of their sides when the materials have a more or less homogeneous texture with no structural abnormalities and, if bedded, when the planes lie in more or less horizontal planes. Noncohesive materials cannot be expected to remain standing in angles steeper than their angle of repose, but when porous and self-draining, such as sand and gravel, they will retain a slope almost equal to their angle of repose. Cohesive materials show a tremendous variation. Those that need quarrying, such as granite, will remain stable with almost vertical sides. Clays, on the other hand, which can initially be dug with vertical sides, have a very low permanently safe slope. This instability is due to shrinking when dry and swelling when wet, which quickly lead to disintegration; the destructive effects of frost; and the plastic char-

*Table VII. Stable cut and fill slopes*

| Material | Climatic conditions | | | | | |
|---|---|---|---|---|---|---|
| | Combined rain and heavy frost | | Rain but not much frost | | Arid regions, not much frost | |
| | Cut | Fill | Cut | Fill | Cut | Fill |
| Sand | 1½:1 | 1½:1 | 1½:1 | 1½:1 | 2:1 | 2:1 |
| | 2:1 | 2:1 | 2:1 | 2:1 | 4:1 | 4:1 |
| Gravel | | | 1½:1 | | 1½:1 | |
| | 1½:1 | 1½:1 | 1:1 | 1½:1 | 1:1 | 1½:1 |
| | 1½:1 | 1½:1 | 1½:1 | 1½:1 | 1¼:1 | 1½:1 |
| Loam | 1½:1 | 1½:1 | | 1½:1 | 1:1 | 1½:1 |
| Clay | 2:1 | 4:1 | 1:1 | 3:1 | ¾:1 | |
| Boulders and earth | 1½:1 | 1½:1 | 1:1 | 1½:1 | 1:1 | 1½:1 |
| Large rock slabs extending back into hill and earth. | 1:1 | 1½:1 | ¾:1 | 1½:1 | ¾:1 | 1½:1 |
| Disintegrated rock and shale. | ½:1 | 1½:1 | ½:1 | 1½:1 | ½:1 | 1¼:1 |
| Solid rock | ¼:1 | 1:1 | ¼:1 | 1:1 | ¼:1 | 1:1 |

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acter of clays, which allows them to squeeze out slowly under load.

(2) Typical safe slopes in homogeneous soils and rocks are shown in table VII.

*b. Relationship of Structures to the Cut Bank.* The following factors lower the permissible angle of slope in the sides of open excavations and demand special precautions.

(1) *Dip of strata.* Where a stratified formation dips down toward the open side of an excavation, there will always be a tendency for the bedding planes to act as surfaces upon which the overlying rock can slide into the cutting. This effect is controlled also by several other factors, such as interbedding, ground water, and the incidence of joints and faults. A general rule, however, is that a series of rocks inclined downward toward the center of the excavation is less stable, and therefore demands a lower angle of slope than a series of horizontal beds or strata dipping away from the cut face (①, fig. 148).

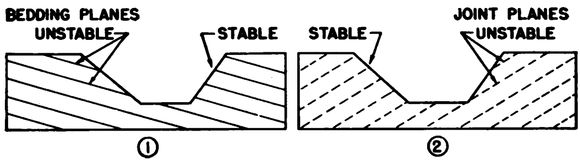


*Figure 148. Effect of jointing and bedding on cuttings.*

(2) *Variation of strata.* Instability of slope is likely to be much worse when different rock types alternate with each other. For example if a uniform slope is made on a formation with interbedded sandstone and clay, the different angles of repose of the two materials will cause the clay to crumble and slide, thus undermining the sandstone and giving rise to rock falls.

(3) *Joints.*

(*a*) Rocks which are traversed by many closely spaced joints are less stable than those with few. If the joints are so numerous that the rock can be quarried only in pieces an inch or so in size, the angle of slope is not much greater than that for an incoherent material such as gravel. Normally, however, hard rocks are not so broken as this and

the greatest danger lies in a restricted number of major (master) joints which may form continuous planes for long distances both laterally and vertically. These joints are potential slide surfaces for landslips.

(*b*) It is usual for master joints to run in one well-defined direction and to be more or less at right angles to the bedding planes in sedimentary rocks. As long as the rocks have not been greatly tilted, the master joints are likely to be nearly vertical and steeper than the sides of the cutting. When the rock has been severely tilted, there will be the same tendency for sliding of a rock mass along a joint face (②, fig. 148) as there is along the bedding plane (①, fig. 148).

(4) *Faults.*

(*a*) Since faults are localized, an initial survey must be made in order to avoid faults or to minimize their effects. They are planes cutting across any bedding and therefore their effects are very similar to those caused by master joints; but they are often more serious. A fault plane is usually well lubricated with clay and smoothed by movement.

(*b*) In a faulted area, several factors must be considered when determining the direction of excavation and the section to be cut. These are direction of the fault, angle of inclination, relation to bedding planes, and water movement. In general, fault zones should be avoided at those places where cuttings are necessary.

*c. Disposition of Surface and Ground Water.*

(1) *Surface water.* Providing adequate surface-drainage is a first essential in protecting the sides of an excavation. Standard civil engineering practice should be followed, although geologic and climatic conditions may have to be considered. In coarse unconsolidated materials, such as conglomerate, the side slopes may have to be left as steep as possible in tropical areas in order to carry off quickly the torrential rains (fig. 149). Similarly, with all types of shale, drainage must provide quick removal of surface water to minimize its action on the rock. Limestone may also be affected by excessive contact with water.

(2) *Ground water.*

(*a*) Ground water encountered in excavating can be both

*Figure 149. Landslide caused by heavy rainfall adding weight and providing lubricant to the soil in a Burma Road cut.*

expensive and hazardous. It is expensive because of the additional equipment needed to dispose of the excess water so that the material can be handled; it is hazardous because it adds weight to the mass, weakens the material by loosening and softening, and increases the mobility of the mass. The problems presented by ground water must be included in the initial geologic studies of an area to be excavated.

(*b*) In unconsolidated material, the best water-bearers are the the most troublesome from an operational standpoint. Gravel and sand may contain considerable amounts of

ground water which they release freely. Yet from the standpoint of stability in the excavation walls, the angle of repose of sand and gravel is only slightly flattened by the presence of ground water. Clay, on the other hand, which has a high water-retaining capacity, shows a great tendency to slide when it becomes water-soaked. Large masses are thus sometimes set loose and flow down to a lower level in excavations worked with a steep face.

*Figure 150. Freezing method used to stabilize water-soaked ground, Grand Coulee Dam, Washington.*

(c) In a mixed series, if a porous rock rests on an impervious one, such as a poorly cemented sandstone on shale, the ground water descending through the sandstone will not only be deflected by the shale, but the wet clay particles carried down to this contact surface will facilitate slipping. If the beds are inclined, a definite seepage line is produced at the line of contact between the two beds, and the porous material resting upon this naturally lubricated plane has a greater tendency to slip.

(d) In consolidated material, except for structural features that influence the safe angle of the cut bank in an excavation (par. 97), ground water is principally an operational hazard. Most of it is borne in cracks or solution channels which in basalt, obsidian, granite, shale, and schist yield in descending order, less water.

(e) Excessive amounts of ground water are usually disposed of by pumping (fig. 142), diverting, or by freezing the water (fig. 150), or by chemically solidifying the water-bearing ground.

## Section III. UNDERGROUND EXCAVATIONS

### 98. General

This section discusses the geologic factors pertinent to underground excavations, particularly those installations for protection of personnel and equipment against aerial attack.

### 99. Military Requirements for Underground Installations

The geologic factors to be considered in the planning stages are evaluated in terms of military requirements. An underground installation must provide security, adequate space, and dryness for the personnel and equipment. Other military considerations of importance are the workability of the natural material and the location of the installation.

*a. Security.* The necessary thickness of the overlying protective layer for an underground installation depends on the type of rock and earth materials, on the degree of soundness of these materials, including such structural features as jointing, on the size and shape of

the underground opening, and on the nature of the bomb or shell against which the protection is desired. Greatest protection is provided by hard, firm rocks and the thickness of the protective layer needs to be least in such rocks. On the other hand, the greatest protective thickness is necessary for structures in soils and soft, friable materials. Experimental work is still continuing on design factors dependent on rock and soil properties. An example of estimates that illustrate the range in protection that natural materials provide can be drawn from Russian design criteria in World War II that called for a roof thickness varying from about 15 feet in granite and limestone to 30 to 50 feet in soil fill for protection against a 220-pound aerial bomb.

*b. Space.* The type and structure of the natural material determine the size and arrangement of the chambers which can be constructed. Openings have to be oriented with relation to jointing so as to leave as little strain as possible on the undercut joint-blocks. Areas in which there is fissuring and shattering due to earth movement, which usually occurs in belts, should be avoided.

*c. Dryness.* The position of the water table in relation to the lower levels of the installation is an important factor in planning for the prevention of wet conditions. More difficult to predict are ground-water conditions that often occur within the tunnel, such as seepage and flooding through fissures, joints, and faults.

*d. Workability of Material.* The type and structure of the natural material determine its workability (response to and ease of drilling for blasting (fig. 151)). Massive materials (consolidated or unconsolidated) with the same properties in all directions are by far the simplest in which to tunnel; the most difficult is material which is faulted or jointed, called "blocky" material. Foliated rocks, such as schist, break easily along planes parallel to the foliation, but break with difficulty at right angles to the foliation. Sedimentary rocks are about equally strong either parallel to or at right angles to the bedding plane but in some, particularly shale, caving and slumping may be pronounced.

*e. Location.* Within the geographic limits established by military needs, the type of rock and topographic form produced will determine the location of an underground installation (pars. 100 and 101).

## 100. Underground Installations in Unconsolidated Materials

*a.* The unconsolidated materials are commonly deposited as alluvium on floodplains and terraces and are found in and along valleys. They

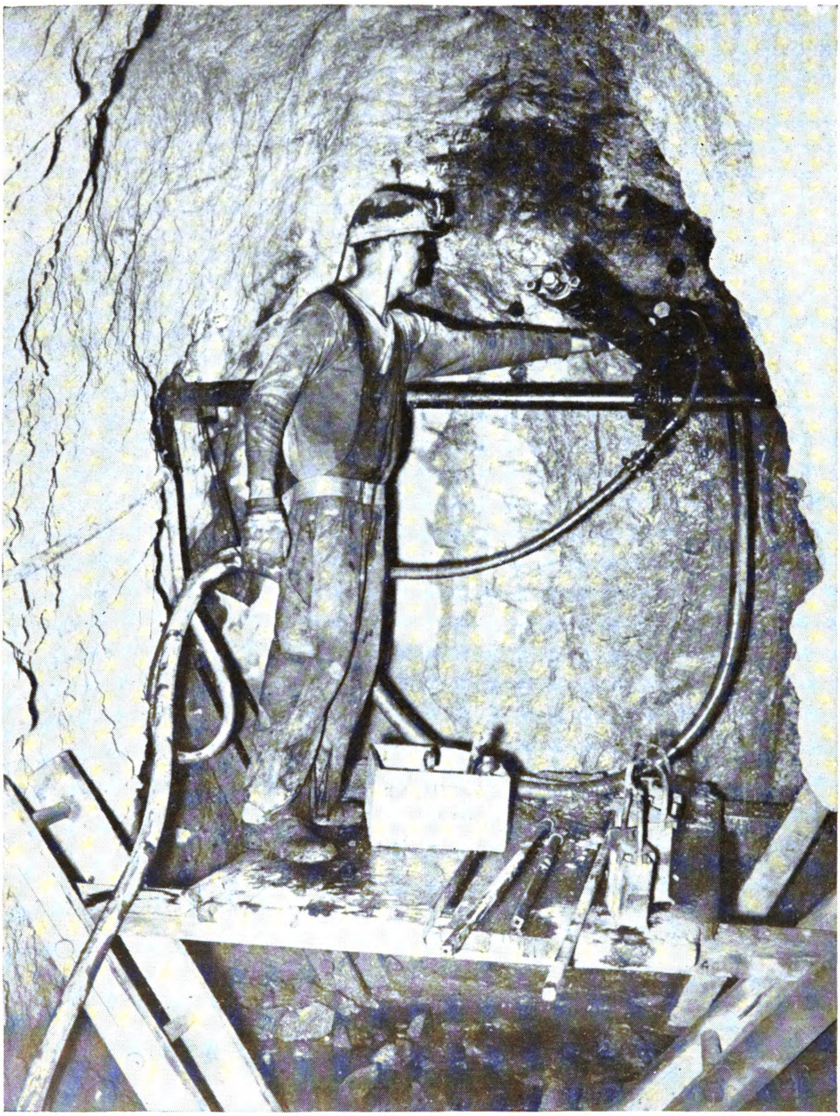

*Figure 151. Drilling blast-holes for an underground excavation. Butte, Montana.*

may exist in topographic forms which are desirable as sites for underground installations and which are easily workable.

*b.* The structure, texture, and stability of unconsolidated materials,

and their behavior when saturated with ground water, usually offset their desirable properties, except under special conditions. Their stability ranges from adequate down to unsuitable except in emergencies. Additional support is needed in nearly all cases (fig. 152). With the exception of clay, these materials can be expected to admit water to underground installations, either from the surface or from nearby artesian aquifers, unless preventive measures are taken.

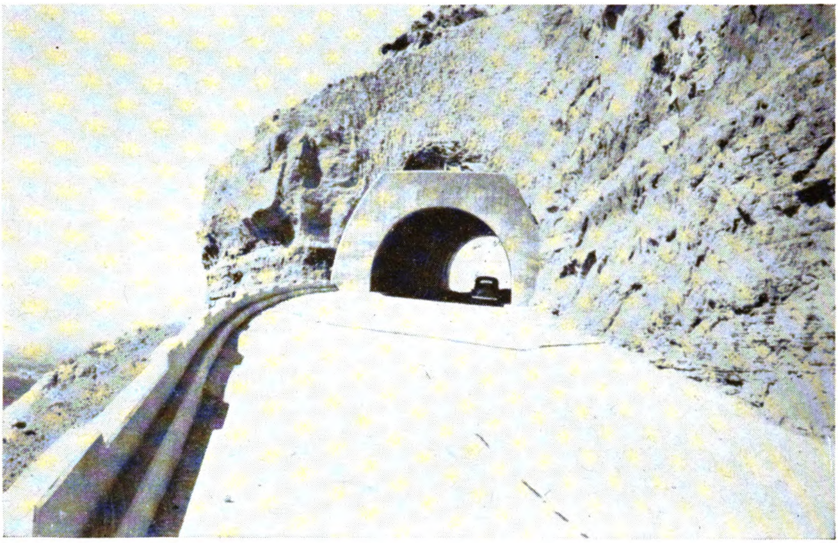

*Figure 152. Tunnel lined to support unconsolidated rock.*

*c.* Small installations, or cave shelters covered in FM 5–15, can be constructed rapidly in unconsolidated materials by mining methods. They require some additional construction materials for roof support, and they are subject to seepage and flooding from surface water and ground water. Gravel and sand combinations are superior to clay and loam in resisting the penetration and the explosive force of high-explosive projectiles and bombs.

## 101. Underground Installations in Consolidated Materials

The consolidated materials, in general, are the best medium in which to construct permanent underground installations. All require mining equipment for their removal. Most reflect structural conditions much

more vividly than the unconsolidated materials. Some are unsuitable as the following discussion of a few common rock types will show.

*a. Sedimentary Rocks.*

(1) *Salt* and *anhydrite* deposits are excellent mediums in which to construct underground installations.

(2) *Limestone* and *dolomite* deposits 10 feet thick or more may offer good sites for underground installations but their hardness requires a longer construction time (fig. 153).

*Figure 153. Tunnel driven through folded limestone in which lining is not required. Blue Ridge Parkway, North Carolina.*

(3) *Sandstone* is one of the more easily worked hard rocks. Since it is less stable than other hard rocks, it requires support after excavation, leading to considerable expense, time, and material. During World War II, the Germans constructed several underground factories in sandstone because of its easy workability. However, rock falls disrupted factory routine and killed personnel. This made the installation of supports necessary, which proved both time consuming and costly. This waste could have been avoided had the installa-

tion been constructed in other rock or had plans been made for proper construction from the beginning.

(4) *Coal* is usually structurally unstable. Coal mines require extensive supports. They often contain harmful gases, and usually have beds too thin to give sufficient head room.

*b. Igneous Rocks.* The igneous rocks, especially basalt, granite, and granite-like rocks, commonly provide satisfactory construction sites for underground installations. Although both granite and basalt contain numerous joints which act as channelways for water, the rocks themselves are virtually impermeable. These rocks have excellent stability and their structural strength is generally high, permitting wide roof spans. Extensive jointing in both granite and basalt helps to counteract explosive forces.

*c. Metamorphic Rocks.* Metamorphic rocks are not generally a suitable medium in which to construct underground installations. Some metamorphic rocks may be fairly permeable. Jointing is common in gneiss and increases its permeability. Stability of metamorphic rocks ranges from excellent to undependable.

# CHAPTER 6

# CONSTRUCTION MATERIALS

## Section I. OCCURRENCE AND USE OF UNCONSOLIDATED MATERIAL (SOIL)

### 102. General

*a.* When unconsolidated material (soil) is classified according to grain size, it is found that there is a critical diameter below which the soil ingredients have some entirely different properties from those of the coarser fractions. On the whole, gravelly and sandy soils are inert and chemically unreactive, with properties dependent on grain size and shape, and to a lesser degree on physical properties such as hardness of the grains. The finer fraction of clay and organic material is chemically and physically reactive. Soils containing them in quantity swell and become plastic when wet and shrink and become cohesive when dry.

*b.* Recognizing the physical behavior of clay and organic matter and how it affects construction material, the Department of the Army has developed a soil classification system (table IV) based on both grain size and plasticity. The characteristics of the different soils as construction materials in subgrades and base courses of roads and runways are based on this engineer soil classification.

### 103. Field Tests for Plasticity

Field appraisal of the engineering suitability of an unconsolidated material becomes largely a problem of estimating the clay and organic content. A dependable field estimate is often difficult to make, and such an estimate is normally not a substitute for the techniques available in the modern testing laboratory. Nevertheless, a few rule-of-thumb methods are useful in a field reconnaissance.

*a. Unconsolidated Material with High Clay Content,* in a moistened condition, has a high degree of plasticity as evidenced by its susceptibility to kneading (fig. 154). Plasticity also is indicated by the *ribbon test,* which is performed by placing a ball of kneaded soil between the thumb and index finger and drawing the index finger under the

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thumb as in closing the hand. Clay will form a long, thin flexible ribbon that does not break under its own weight. When dry, intense finger pressure is required to break up the sample. Such soils are usually inferior for construction.

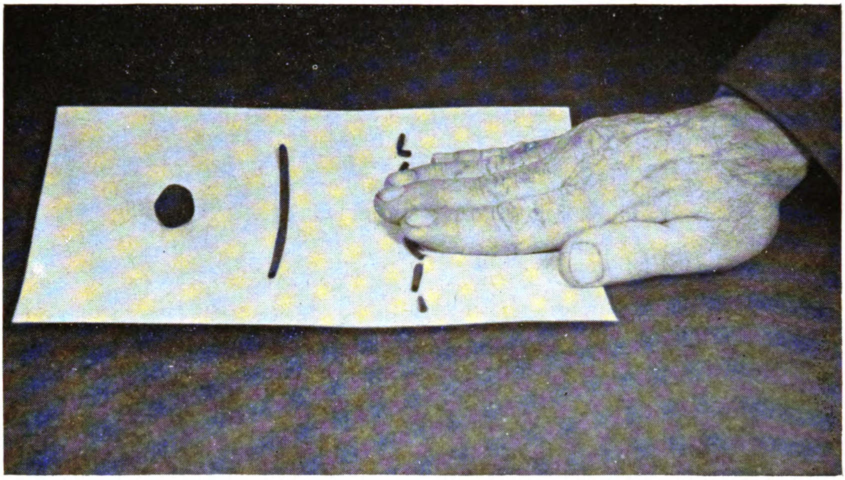

*Figure 154. Kneading test used to classify clays.*

*b. Unconsolidated Material High in Organic Matter* has a black or dark blue color, and is generally unsatisfactory for construction. Such soil is common in swamps and depressions where peat accumulates or where drainage is poor.

*c. Unconsolidated Material Containing more Silt than Clay* has a silky feel and little plasticity when wet. Unless well-drained, it is to be avoided for construction, particularly in cold and wet climates. Two field tests are used in the identification of this material:

(1) *Shaking test.* In this test a wet pad of soil is alternately shaken horizontally in the palm of the hand and then squeezed between the fingers. A typical inorganic silt will become "livery" and show free water in the surface while being shaken (fig. 155). Squeezing will cause the water to disappear from the surface and the sample to stiffen and finally crumble under increasing finger pressure, like a brittle material. If the water content is just right, shaking the broken pieces will cause them to liquefy and flow together.

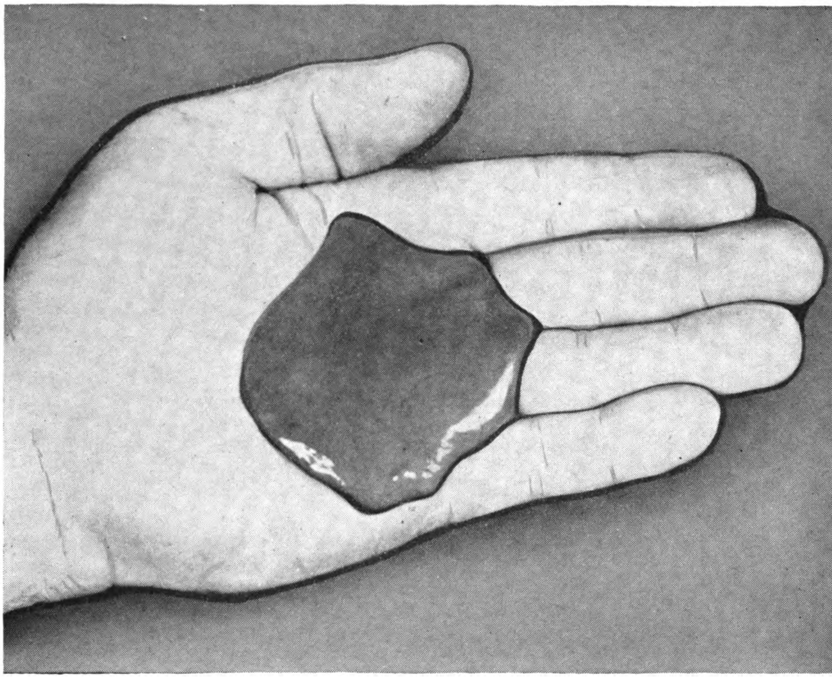

*Figure 155. "Livery" appearance of silt in shaking test.*

(2) *Breaking test.* When the sample is dry, it becomes friable, easily crumbled in the fingers. Typical silt shows little or no cohesion when dry and feels smooth in contrast to the grittiness of fine sand, for which it is sometimes mistaken.

*d. Unconsolidated Materials That Have a High Sand Content* are not plastic when wet and crumble when dry. They feel gritty, and the grains may be seen either directly or with a low-powered lens. In combined materials consisting of sand, silt, and clay, the material with the higher sand and silt content is more desirable for embankments and fills. The same is largely true for foundation materials, except that a practically pure sand is undesirable for a foundation when the water table is close to the surface.

## 104. Clay and Clayey Soil as a Construction Material

*a. Occurrence.*

(1) When clay is needed, the soil of an area should be considered first, because it may be high enough in clay content to serve

the purpose. To find large deposits of a fairly pure grade of clay may require a long and careful search.

(2) Seams and pockets of clay will invariably occur in sand and gravel deposits in river bars, banks, and terraces. Swamps, depressions, low flat areas, river valleys, and dry lake basins are likely sources. Marshes and places covered by thick tule growths often contain clay and other fine sediment. In areas of deep and pronounced rock decay, clay may be found lying directly on the rocks from which it is formed. Such residual clays may occur in humid regions and are commonly formed from thick-bedded or unstratified massive rocks rather than from layered rocks.

*b. Uses.*

(1) *General.* Clay functions primarily as a binder. A clay with a medium plasticity index is the most desirable for this purpose.

(2) *Properties which limit use.* Clay and clayey soil have properties that limit their desirabiliy as construction material,

*Figure 156. Loss of supporting power in clay due to excessive vehicular traffic after a rain. Okinawa.*

especially when used in embankments and fills. These properties are:

(*a*) Marked shrinking and swelling with variation in moisture content.

(*b*) Moisture retention for a long period of time.

(*c*) Tendency of the surface to become semiliquid or viscous under load when exposed to the action of rain or surface waters for some time (fig. 156).

(*d*) Loss of supporting power when reworked by vehicular traffic or other action.

## 105. Sand and Gravel as Construction Material

*a. Occurrence.*

(1) *General.*

(*a*) Sand originates from fragments of solid materials which have been worn into smaller pieces while being transported or when left as residual deposits. Although quartz is by far the most common constituent of sand, many minerals may be present or even predominant. For example, great deposits of gypsum sand are found in New Mexico; many Pacific island beaches are composed of coral sand (limestone).

(*b*) Sand grains vary in shape from round to subangular to angular. The degree of roundness usually depends on the hardness of the material, the transporting agent, and the distance the material has been transported. Sand grains in the upper reaches of a stream are usually more angular than those farther downstream. Glacial and residual sands are usually angular, whereas wind-blown (or aeolian) sands are much more rounded. Very small grains are usually not well-rounded.

(2) *Stream deposits.* The beds and banks of rivers and streams are the most common sources of sand and gravel. Little can be done with materials in the main channel of a deep river without special equipment; but river banks, bars, terraces, and floodplains offer good prospects for surface pits. Bar gravels (fig. 157) and sands are, as a rule, freer of silt, clay, and organic debris than bank or terrace deposits (fig. 158); moreover, there is usually no overburden.

*Figure 157. River-bar gravel.*

*Figure 158. Terrace gravel. Casco Airfield, Alaska.*

(3) *Glacial deposits.* In glaciated regions, the esker (fig. 58) and kame terrace (fig. 159) are the best sources of sand and gravel, and are easily prospected. In other types of glacial deposits, such as moraines, the material is usually so poorly sorted that it is almost useless, and the amount of screening, washing, and other treatment needed to obtain usable sand and gravel is prohibitive.

(4) *Wind deposits.* Dune sand deposits are widespread in deserts. They are occasionally found along sea and lake

*Figure 159. Kame terrace material. Casco Airfield, Alaska.*

shores, in large river valleys, and in the beds of dry lakes. These wind-deposited sands are characteristically finer-grained than typical river sands, and are not as good for construction purposes.

*b. Uses.*

(1) *General.* Sand and gravel intended for construction use should be considered as to size, gradation, quality, type of parent rock or rocks, and the clay content.

(2) *Subgrade.* The sand and gravel particles in the subgrade should be fairly hard. The amount of binder or the binding action of the aggregate particles themselves depends on the clay content and the material composition. The bearing capacity of the material under varying conditions of moisture content depends on the strength of the particles and the bond or friction between them when unconfined.

(3) *Base course and surfacing materials.* For base course and surfacing materials, quality becomes more important. Gravel should be reasonably free of soft, friable, or flaky particles; sand should be composed of fairly sharp, angular grains. Both sand and gravel should be comparatively free from coal, alkali, mica, gypsum, and water-soluble salts or coatings. Gravels which range in size from 1/4-inch to 3-inch diameters are preferred to gravels of uniform size. Flat and elongated pieces are to be avoided. Well-rounded particles do not always bind well. Subround or cubical shapes are

more desirable. Gravels derived from dark-colored igneous rocks bind better than gravels from light-colored igneous rocks but the latter, when partly disintegrated, often bind well and are more easily excavated. The partly decomposed dark igneous rocks usually bind excellently but, if they are too much decomposed, their high content of clay may impair their wearing properties. Limestone gravels bind better than quartzite or quartz gravels. Since the binding properties of sandstone gravels depend on widely varying cementing matrixes, they exhibit a wide range of bond. Shale gravels, slate gravels, and other gravels consisting of flat, flaky-shaped particles are not desirable. The amount of clay binder in the material can often be judged by the slope of the gravel bank or outcrop. If other qualities are satisfactory, a gravel face that will stand at a nearly vertical slope usually contains enough clay to make good base course and surfacing material.

(4) *Embankment and fill.* For embankment and fill, mixtures of sand and gravel of almost any quality are acceptable, provided they contain sufficient clay binder to hold the mass in place. Material of uniform particle size is not as desirable as material having particles ranging from coarse to fine. Flat and flaky particles are generally undesirable.

(5) *Concrete aggregate.*

(*a*) For concrete aggregates, quality and gradation of gravel and sand are both very important. Clay and organic materials are harmful because they coat the particles and hinder the binding action of the admixed cement. The grading requirements are usually predetermined so that maximum strength of the concrete will be attained. The aggregate should possess strength equal to and preferably greater than the cement. Clean, hard, durable particles free from injurious substances are ordinarily specified. This means that, in practice, gravel and sand composed of almost any variety of dense, sound, igneous rock can be made into satisfactory concrete. Some metamorphic and sedimentary rocks are objectionable (par. 108).

(*b*) The statements made concerning the use of ledge rock for concrete aggregate apply in the main to sands and gravel derived from the rock types discussed in paragraph 108.

## Section II. OCCURRENCE AND USE OF CONSOLIDATED MATERIAL (ROCK)

### 106. General

Ledge rocks often occur in thick massive layers and, for most uses, such rock has to be crushed (fig. 160). Problems involved in blasting, excavation, crushing, and wastage must be considered. Such problems are peculiar to each variety of rock and to individual localities where the same variety occurs.

*Figure 160. Irregularly jointed rock used as source for crushed rock.*

### 107. Occurrence

A study of the terrain, or of a topographic map of an area, will readily suggest localities where consolidated materials can be obtained for engineering construction. A summary of the distribution of the major rock types is presented in paragraph 11*c*.

### 108. Uses

*a. Embankment and Fill.* Ledge rock is not much used for em-

bankment and fill except where readily available and easy to handle. If ledge rock is especially desirable, the main requirement is that the rock be sufficiently coherent to withstand removal and transportation. Composition is generally not very important. Firm, hard rock is the most desirable although it is usually most difficult to quarry. Shale, clay shale, limestone containing clay, gypsum rock, mica schist, and rocks that contain much water-soluble salt are not desirable, especially in humid regions or where the rock is continually exposed to moisture or water.

*b. Base and Surface Courses.* Rock from ledges must be crushed. The shape, size and quality of resulting particles are important (par. 105). For water-bound macadam, shale and slate should never be used because of their high clay content. The low binding properties of granite, gneiss, schist, sandstone, and quartzite frequently make these rocks unsuitable. The type of construction largely limits the requirements. A type of rock that is unsuitable for water-bound macadam, because of poor binding properties, might be entirely satisfactory when used for bituminous macadam or concrete surface course. For this reason, the qualities of rocks (par. 15) rather than types of rocks are specified for base and surface courses. For example, a hard, tough, durable type is needed for the wearing course.

*c. Concrete Aggregate.*

(1) *Igneous rock.* Testing and research work on samples of igneous rocks from the entire United States have established the following principles:

(*a*) The fine-grained igneous rock aggregates are generally harder and tougher than coarse-grained igneous rock aggregates.

(*b*) The dark-colored basic igneous aggregates (trap rocks) possess good wearing qualities because of their toughness and high resistance to abrasion.

(*c*) The glassy volcanic rock particles, such as obsidian, do not bond well with cement if glassy surfaces are exposed, although the bond will be better if the surfaces are worn rough.

(*d*) The volcanic-flow rocks, such as rhyolite, may be undesirable since they tend to form particles that have a flat, chiplike, or elongated shape.

(*e*) The porous varieties of igneous rock, such as pumice and

scoriaceous basalts, are less desirable than the dense varieties, because of their low specific gravity and their susceptibility to disintegration by freezing, thawing, and weathering.

(2) *Sedimentary rocks.* The results of work done by the United States Public Roads Administration provide a basis for generalizations about the durability of sedimentary rock aggregates as follows:

(*a*) Limestone, dolomite, and sandstone are, as a rule, appreciably softer and less tough than the igneous rocks.

(*b*) A great range in hardness and toughness may be exhibited by different sandstone beds. Sandstone may be as tough as limestone and dolomite, but is usually less resistant to abrasion.

(*c*) Most shale and other clayey rocks are soft, weak, and nondurable.

(*d*) Mixtures of soft and hard sedimentary rocks usually require laboratory testing to determine their durability.

(3) *Metamorphic rocks.* Aggregates composed entirely or largely of metamorphic rocks also exhibit wide variations in physical properties.

(*a*) Marble is generally softer and less tough than limestone.

(*b*) Slate is soft, weak, and nondurable.

(*c*) Quartzite is usually extremely hard, tough, and resistant to abrasion. In many respects, it compares favorably with trap rock.

(*d*) Gneiss and schist correspond more closely to granite, except when they break into thin, elongated fragments. In general, when the mica content is high or the planes of separation are weak and closely spaced, the material may be as lacking in strength, as is the case with some varieties of shale.

*d. Riprap and Rubble.* The rock used for riprap and for rubble masonry must meet requirements similar to those for base and surface-wearing course material. Since rock for riprap must be available in large sizes, the shape, condition, and quality of each piece of rock are of concern to the construction engineer. Riprap rock should be free from planes of weakness and have not only a fairly high specific gravity but also resistance to water scour and weathering. Therefore, massive, compact, fine-grained, igneous rocks that are fresh, un-

weathered, and unfractured are used when available. Rocks, such as limestone, do not resist scour and other water action as well as granite and trap rock, which are preferred for marine work. The sedimentary rocks, in general, are inferior in hardness, toughness, and soundness to the igneous rocks. The bedding of sedimentary rocks is favorable to quarrying, but it may limit the thickness of the blocks obtainable. The tendency of gneiss, schist, slate, and other metamorphic rocks to fracture or to cleave into layers is likewise a frequent obstacle to obtaining blocks large enough for riprap.

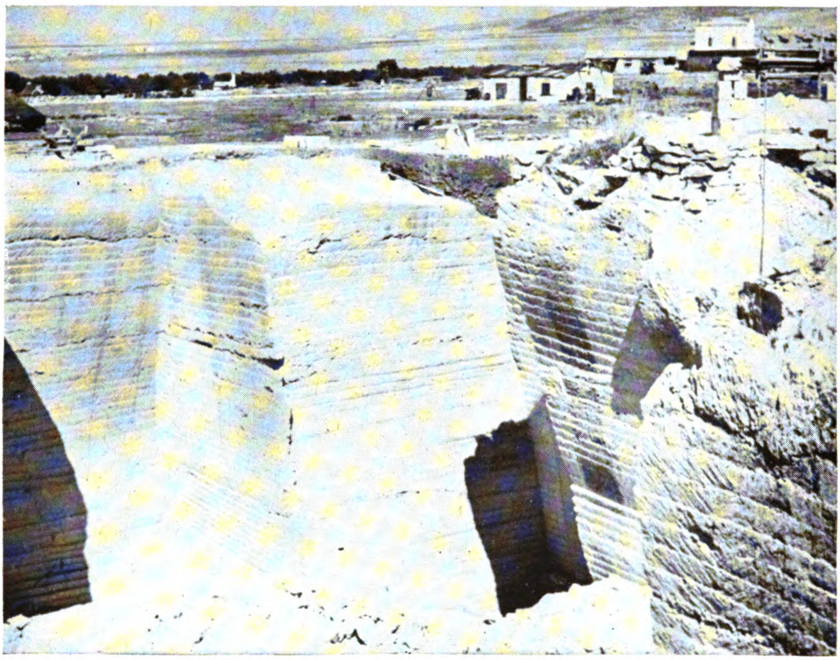

*Figure 161. Tuff quarry near Amendola, Italy.*

## Section III. OCCURRENCE AND USE OF SPECIAL LOCALIZED MATERIALS

### 109. Tuff as a Construction Material

*a. Occurrence.* Tuff is commonly found in regions where volcanic action has taken place. Occasionally, however, wind action has spread

*Figure 162. Surface course of tuff, Amendola Airfield, Italy.*

a deposit from a single, active source over an area of thousands of square miles. It is found in the mountainous regions of western North and South America, in southern and central Europe, in northern Africa, on the east coast of Asia, in Alasaka, on many islands in the southern and western Pacific, and in Italy (fig. 161).

*b. Uses.*

(1) Tuff was used during World War II for the construction of access roads, hardstands, taxiways, and runways at the Amendola airfield in east central Italy (fig. 162). The tuff used there was a soft, workable rock, which was loosened by tractor-drawn rooter and stockpiled with bulldozers.

(2) Block tuff was also used at the Amendola airfield in the construction of buildings.

## 110. Caliche as a Construction Material

*a. Occurrence.*

(1) Deposits of caliche are formed in arid or semiarid regions where salts are brought to the earth's surface by rising waters. After the water evaporates, the salts remain on the surface or in the surface materials. These deposits are known by different names in different regions: *tepetate, alkali,* and

*hardpan* in different parts of the United States; *reh* in India; and *sabach* in Egypt.

(2) In southern and southwestern United States, the term *caliche* is used to mean any surface or near surface hardpan which has been cemented by mineralized solutions. It may be fine or coarse in texture, fragmental or thoroughly cemented. The cementing material is most commonly calcium carbonate with calcium, sodium, and potassium sulphates common, and calcium and sodium chlorides and sodium carbonate not uncommon.

*b. Uses.* The wide variation in both the content and the degree of cementation in caliche accounts for the differences of opinion concerning its suitability for road or runway construction or for aggregate. The suitability of each deposit should be determined by tests. Caliche is often fairly uniform over considerable areas where the surface soils, sands, or gravels are of relatively uniform character and are saturated by more or less similar cementing solutions. One quality which makes many caliches valuable for road construction is their tendency to recement after being saturated with water, compacted, and allowed to set. This is especially applicable to caliches which are cemented with lime or salt.

*Figure 163. Hard coral used in road and airfield construction. Saipan Island.*

## 111. Coral as a Construction Material

*a. Occurrence.*

(1) *Geographic distribution* (fig. 128). The geographic distribution of reef-building corals apparently is controlled by the supply of clear, warm water needed for their development. The majority of the coral reefs occur within 25° of latitude north and south of the equator, the limit being about 30°. Coral reefs flourish in the Indian Ocean and Pacific Ocean, except along the coast of North and South America. They are well-represented in the West Indies, but are absent elsewhere in the Atlantic Ocean.

(2) *Local deposits.* For military construction, reef coral is divided into two general groups: hard coral (class 1) and soft coral (class 2).

(*a*) *Hard coral* (*class 1*) is formed by the intergrowth of coral heads and the cementation of coral sand and fragmental reef materials. It is commonly massive, but may range from porous to dense depending on the manner of cemen-

*Figure 164. Soft coral used in construction of runway on Kwajalein, Marshall Islands.*

tation. It is usually white but may be gray-white, buff, yellow, or brown. Chemically, it is principally calcium carbonate but often contains chert, gypsum, and streaks of clay. It occurs as reefs, beach ledges, or elevated terraces (fig. 163). It may require quarrying for use as a structural material and, on account of fissures, and veins of clay and soft coral which may be present, it may be difficult to blast. It usually requires crushing.

(*b*) *Soft coral* (*class* 2) consists of unconsolidated muds, sands, fragmental coral, algal deposits, shells, or the product of the partial weathering of hard coral. Physically it is earthy or marly and erodes to rounded slopes. It may vary from loose to compact, being not especially cohesive when dry. In color it is white, gray, buff, yellow, brown, or light chocolate brown. It occurs in a muddy or plastic

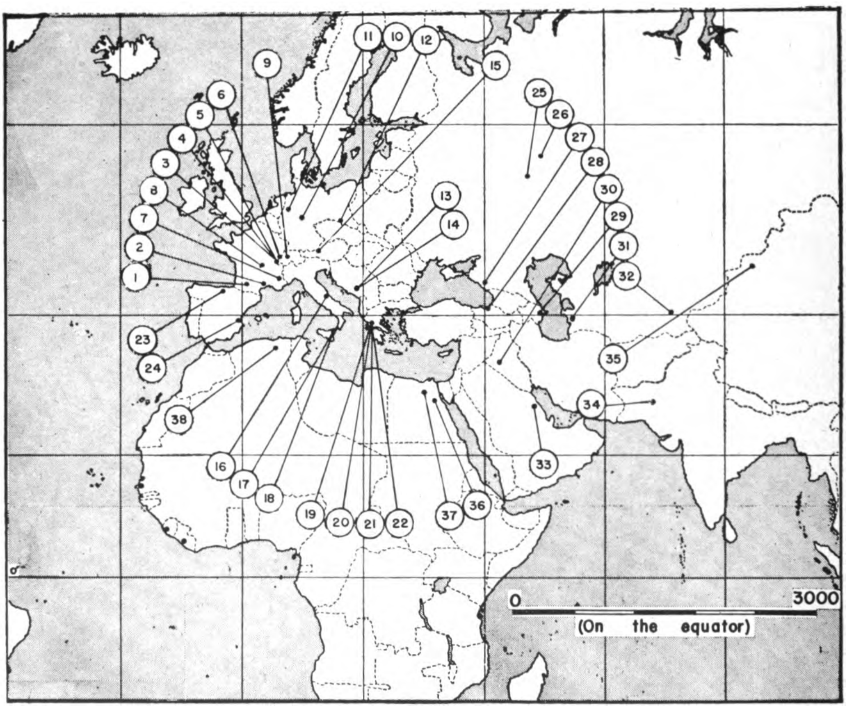


*Figure 165. Natural asphalt deposits in Europe, Asia, and Africa.*

state in lagoons or near shallow water (fig. 164) and in a more compact state as interreefs, as beach ridges, or as elevated terraces. It is usually easily worked in pits or on terrace slopes with rooters, pans, bulldozers, or shovels.

*b. Uses.*

(1) *Fills, subgrades, and base courses.* When properly placed, selected coral, stripped from lagoon or beach floors or quarried from side hills, is excellent for fills, subgrades, and base courses.

(2) *Surfacing.* White or nearly white soft coral with properly proportioned granular sizes compacted at optimum moisture-content will create a concrete-like surface. The wearing surface will require considerable care and maintenance.

(3) *Concrete aggregate.* Hard coral, when properly graded, is a good aggregate for concrete. Soft coral makes an inferior

| | Lat. | Long. | Matrix (*) |
|---|---|---|---|
| | *France* | | |
| 1. | 43°25′ N. | 0°29′ W. | Sand |
| 2. | 44°16′ N. | 4°18′ E. | LS. |
| 3. | 46°01′ N. | 5°58′ E. | LS and SS. |
| 4. | 46°01′ N. | 5°57′ E. | LS and SS. |
| 5. | 45°54′ N. | 6°02′ E. | LS and SS. |
| 6. | 46°07′ N. | 5°50′ E. | LS. |
| 7. | 43°58′ N. | 5°45′ E. | LS. |
| 8. | 45°48′ N. | 3°21′ E. | |
| | *Switzerland* | | |
| 9. | 47°00′ N. | 6°48′ E. | LS. |
| | *Germany* | | |
| 10. | 51°57′ N. | 9°38′ E. | LS. |
| 11. | 51°58′ N. | 6°32′ E. | LS. |
| 12. | 50°57′ N. | 16°20′ E. | Granite. |
| | *Jugoslavia* | | |
| 13. | 42°41′ N. | 18°01′ E. | LS. |
| 14. | 42°55′ N. | 18°00′ E. | LS. |
| | *Austria* | | |
| 15. | 47°19′ N. | 11°11′ E. | Shale. |
| | *Italy* | | |
| 16. | 42°01′ N. | 13°57′ E. | LS. |
| 17. | 36°56′ N. | 14°44′ E. | LS. |
| 18. | 36°42′ N. | 15°05′ E. | Basalt. |
| | *Greece* | | |
| 19. | 37°31′ N. | 21°29′ E. | |
| 20. | 37°47′ N. | 20°55′ E. | Lqd. asphalt |
| 21. | 39°12′ N. | 20°10′ E. | LS. |
| 22. | 39°08′ N. | 20°16′ E. | LS. |

| | Lat. | Long. | Matrix (*) |
|---|---|---|---|
| | *Spain* | | |
| 23. | 43°17′ N. | 3°29′ E. | LS. |
| 24. | 38°52′ N. | 0°43′ W. | |
| | *Russia* | | |
| 25. | 53°06′ N. | 48°20′ E. | Dol. and SS. |
| 26. | 55°19′ N. | 50°32′ E. | |
| 27. | 43°04′ N. | 40°58′ E. | DOL. |
| 28. | 41°54′ N. | 42°04′ E. | SS. |
| 29. | 40°25′ N. | 50°00′ E. | |
| | *Iraq* | | |
| 30. | 33°38′ N. | 42°53′ E. | LS. |
| | *Russia* | | |
| 31. | 39°30′ N. | 53°10′ E. | |
| 32. | 40°00′ N. | 71°00′ E. | |
| | *Arabia* | | |
| 33. | 26°00′ N. | 50°35′ E. | Ash. |
| | *India* | | |
| 34. | 28°32′ N. | 67°32′ E. | Asphalt seeps. |
| | *China* | | |
| 35. | 45°38′ N. | 85°28′ E. | |
| | *Egypt* | | |
| 36. | 27°59′ N. | 33°21′ E. | |
| 37. | 29°48′ N. | 31°24′ E. | SS. |
| | *Algeria* | | |
| 38. | 36°12′ N. | 6°45′ E. | LS. |

(*) Material with which natural asphalt occurs.

*Figure 165.—Continued*

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concrete, low in strength, difficult to place, and often of honeycomb structure.

## 112. Natural Asphalt as a Surfacing Material

*a. Occurrence.*

(1) *Geographic distribution.* Deposits of natural asphalt of varying types and sizes may be found in almost every country in the world. The extensive deposits are, however, generally associated with areas which have not been subjected to severe deformation.

(2) *Local deposits.* Naturally occurring asphalt deposits can be roughly grouped into three types: surface pools and seeps; subterranean pools and deposits in porous rock (rock asphalt); and solid vein fillings.

(*a*) The pools and seeps of asphalt are the purest and rarest of the natural asphalt deposits. The asphalt may be liquid, semiliquid, or solid. It may often be used with little or no special treatment.

(*b*) Rock asphalt (rock which has been impregnated naturally with asphalt) occurs much more frequently than the purer form ((*a*) above). The asphalt, in a liquid or semiliquid state, commonly occupies solution cavities or cracks in such soluble rocks as limestone and dolomite, and the interstitial spaces between grains in such rock as sandstone. Figure 165 gives the location of some important rock-asphalt deposits.

(*c*) Solid asphalt in veins occurs where the volatile constituents of the asphalt (natural gases) vaporize when exposed to air or heat. Figure 165 gives the location of some important vein deposits.

*b. Uses.* Rock and vein asphalt is used principally for surfacing roads and landing fields. The natural material has to be quarried and crushed, and each deposit has to be evaluated for the use intended. Normally, such a high percent of mineral matter is present that fluxing asphalt will have to be added to satisfy the normal construction requirements. However, when commercial asphalt is scarce or lacking, natural asphalt deposits could be invaluable.

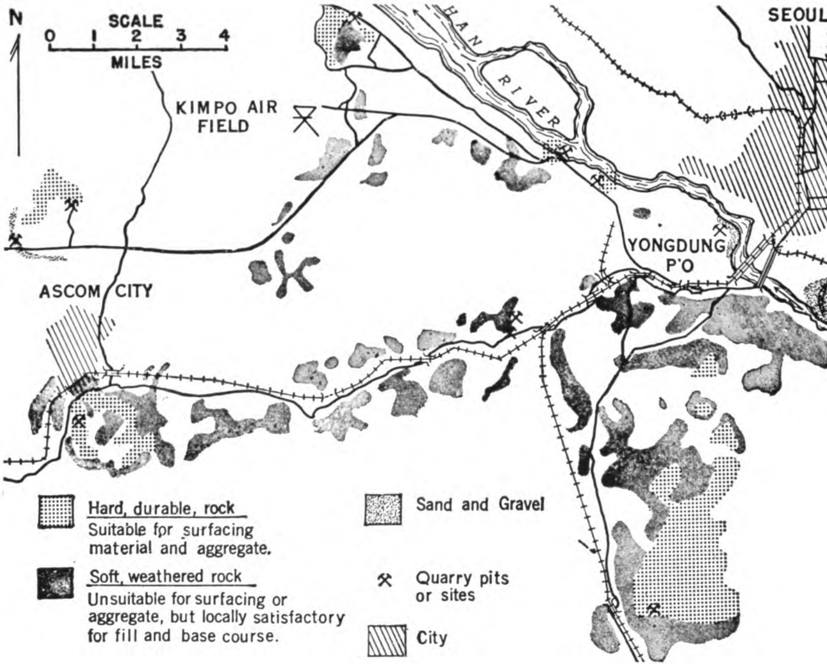



*Figure 166. Construction materials map of Seoul, Korea.*

## Section IV. FINDING THE DEPOSIT

### 113. General

Finding suitable deposits of natural construction materials often requires a considerable amount of prospecting. Thorough preliminary research saves time by limiting the areas to be prospected to those having definite possibilities. When ground reconnaissance is possible, the preliminary research need not be so exhaustive but should not be disregarded, since judicious consideration of the available records will result in a much more efficient reconnaissance.

### 114. Preliminary Aids

*a.* Valuable sources of information on areas to be prospected are geologic maps, topographic maps, or materials maps (fig. 166).

*b.* If maps and other information are lacking, interpretation of the geologic history of an area will usually be a valuable aid in prospecting, since the characteristics of the earth's materials reflect the geologic history of an area.

*c.* Chapter 4 lists possible sources of construction material within the physiographic divisions discussed.

### 115. Field Reconnaissance

The first objective of a field reconnaissance should be to investigate all existing sites of pits and quarries revealed by the preliminary study. If the construction material in existing sites is found undesirable, then rock outcrops, river valleys, and road cuts should be investigated, since they give surface indications of possible supplies of construction materials.

## Section V. EVALUATING THE DEPOSIT

### 116. General

Every effort should be made to study a potential pit or quarry to determine, as accurately as possible, the quality and quantity of material and pertinent operating conditions. Usually time and available equipment limit the extent and accuracy of any field reconnaissance. Time permitting, the factors which should be considered when evaluating a deposit as a possible source of construction material are: proximity and accessibility, overburden, weathering, volume, structure, and surface and ground water.

### 117. Proximity and Accessibility

*a.* Two very important factors to be considered in the evaluation of a prospect are proximity to the work project, and accessibility to available conveyances. Short air distance does not necessarily mean easy accessibility, and the reconnaissance survey should be made with this in mind.

*b.* In the early stages of combat operations where great haste is necessary, those materials near at hand must be used, almost regardless of their quality. If no usable materials are found near a site

for a structure, a new site may have to be selected or a new type of structure may have to be planned. For example, in northern Africa during World War II it was necessary to utilize the local clay soil or "adobe" to make sun-dried brick and to form rammed-earth walls for the construction of small buildings, since tentage, lumber, cement, and suitable rock were not available. This "adobe" proved entirely satisfactory for field use and an emergency housing situation was successfully met.

*c.* When time permits making a deliberate search for suitable earth materials, exploration ordinarily begins at the construction site and extends to whatever may be a reasonable distance from that point. A geologic map of the area is very desirable as a guide to different rock materials. If one is not available, then almost any other map will be of some help for reconnaissance work, and can be used for a base map on which to plot the locations of the various materials.

*d.* Normally, all the deposits of construction material believed to be of adequate volume and of similar quality in the area should be visited and their locations recorded on the base map. Failure to do so may lead to a loss of time and effort resulting from unnecessary transportation distance as shown in the following example (fig. 167): Portable crushing equipment was set up in an abandoned limestone quarry at A for a 3½-mile road-surfacing project at B. The quarry was 3½

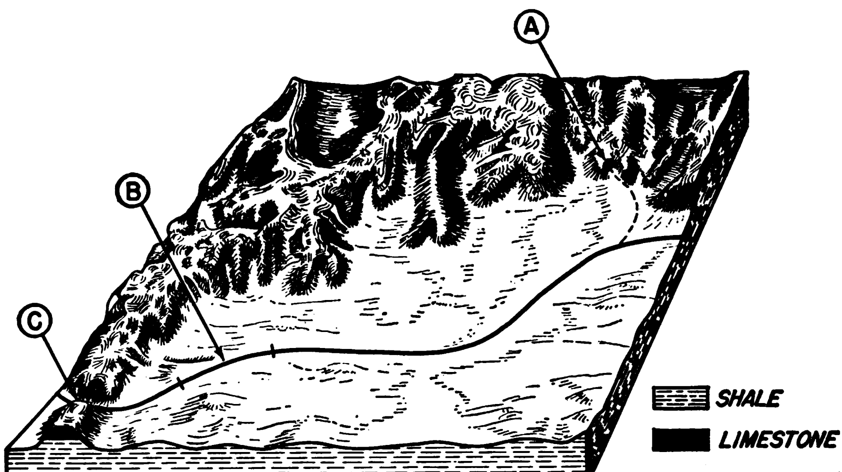



*Figure 167. Block diagram showing relationship of a road-surfacing project (B) to a limestone suitable as surfacing material at a quarry (A) and in a road cut (C).*

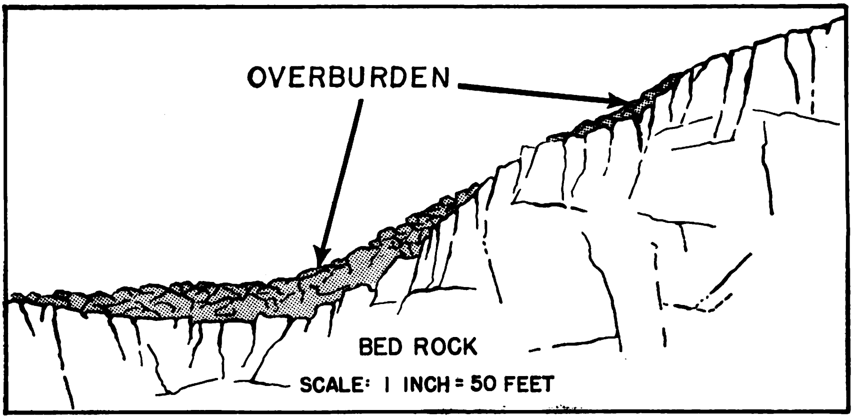



*Figure 168. Cross-section of bedrock showing variation in depth of overburden on slopes.*

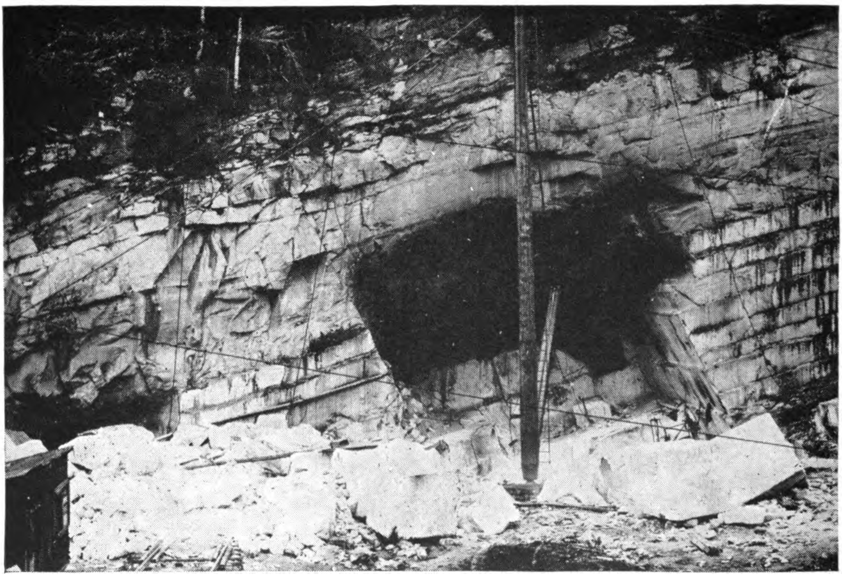


*Figure 169. Quarrying by tunnel to avoid excessive overburden removal.*

miles from the main highway, and the average haul was 17 miles. In the course of the work, too late to be utilized, limestone of the same quality as that in the quarry at A was found along the highway in a cut at C, approximately 4 miles from the near end of the surfacing job. The geologic principle overlooked in the field reconnaissance,

if one was made, is that a sedimentary rock such as limestone can extend over a considerable area without appreciable change in character. A geologic map would have showed the lateral distribution of the deposit. Even an evaluation of the terrain would have dictated the need for an investigation of site C before the crushing equipment was set up at A.

## 118. Overburden

*a. Definition.* The waste material overlying a usuable deposit is referred to as *overburden.* The term is commonly applied only to loose materials (fig. 168), but locally it may include solid rock lying above some desired material (fig. 169).

*b. Factors Determining Depth of Overburden.* The depth and type of overburden are influenced by complex and varied conditions, the major factors being climate, kind of bedrock, and topography.

(1) *Climate.* Heavy rainfall and high temperatures, such as those in the humid tropics, promote rapid weathering at great depths. In Nicaragua, for example, 200 feet of residual overburden was reported in one locality, and in Brazil, 400 feet. Sound rock is rarely found near the surface in such climates. In drier, cooler climates, weathering is slower and residual overburden tends to be thinner. In arid climates, residual overburden is usually thin or absent.

(2) *Kind of bedrock.* The thicker residual overburden is usually found on the less resistant kinds of bedrock, other things being equal.

(3) *Topography and structure.* In a given set of climatic conditions and a given type of bedrock, the thickness of the residual overburden depends on the slopes. It is usually thinnest at the tops of slopes, and gradually thickens downhill, being much thicker on gentle slopes than on steep hillsides (fig. 168). Similarly, in regions of folded structure, the overburden is deepest in the troughs of syncline valleys and shallowest on the crests of the anticlines.

*Importance of Overburden.* The overburden is an important consideration in evaluating a construction material prospect. If the overburden is too thick, or proves difficult to remove, the time required and the effort lost in the operation may become prohibitive, unless

a use can be found for the overburden as well as the underlying material.

## 119. Weathering

*a. Effect of Weathering on Construction Material.* Mechanical weathering alone usually does not seriously impair the quality of rock for construction use, but it may reduce the size of the rock fragments so that the use is limited thereby. Extensive chemical weathering, on the other hand, may make rocks less suitable for most structural uses because it usually increases their porosity and decreases their toughness, compressive strength, resistance to abrasion, soundness, and specific gravity.

*b. Estimating the Degree of Weathering.*

(1) The amount of weathering in rock can usually be estimated in the field. During reconnaissance, all exposed ledges should be examined for discoloration in the rock which may indicate the beginning of decay. The debris along the face of the ledge and in old quarries should be studied to determine the quality of the weathered material, since some rocks that appear sound when in place disintegrate very rapidly upon short exposure to the atmosphere. Fresh solid rock resounds with a clear tone when struck by a hammer. It shows lustrous minerals in the freshly broken surface. It is broken with difficulty, and in an igneous rock the break cuts across mineral crystals. Soft and weathered rocks have a dull appearance; break easily when struck with a hammer; and shed grains and stain the fingers when rubbed.

(2) When a large mass of material is needed, it may be necessary to conduct drilling operations to prove the suitability of the deposit.

## 120. Volume of Deposit

*a.* A detailed evaluation of volume may require borings to prove the thickness of the deposit. Test pits or trenches are also useful for this purpose if labor and time permit.

*b.* It is advisable on any construction project to have more volume of material available than is actually required. Unforeseen difficulties may arise in excavation. For example, the quality of the material may become poorer as excavation progresses, or a water table

or springs may be encountered. Any of these factors may reduce the volume estimate. For this reason, volume estimates should be somewhat conservative.

*c.* On the other hand, when either consolidated or unconsolidated material is removed it has greater volume than it did before excavation, the amount of increase depending on the type of material.

## 121. Structure

Secondary structural features, such as faults, folds, and joints, and primary features, such as bedding, have an important bearing on the recovery of construction material, and in some instances may seriously affect its quantity, quality, and use.

*a. Faults.*

(1) Rock in a fault zone is usually badly shattered and pulverized. Sometimes this rock is usable, especially for aggregate and surfacing material. As a rule, however, fault-zone rock is not acceptable as construction material because it contains too much pulverized rock or too many clay seams (gouge pockets); it is often contaminated by admixture of weathered rock; and it is susceptible to more intense weathering since a greater surface area is exposed to air and water.

(2) In layered rock, the total displacement of usable material may be so great at times, that the supply of the desired construction material abruptly ends at the fault, without a reasonable possibility of utilizing the continuation of any part of the layer.

(3) Since faults act as paths for the passage of ground water, springs commonly occur in fault areas and create operational hazards.

*b. Folds.*

(1) Excavations are frequently made without reference to the fact that gentle folding exists because the zone of excavation and quarrying is not significantly disturbed by variations in dip or in the thickness of individual layers.

(2) Sharp or close folding in bedded rock, on the other hand, presents quarrying problems because the dip changes abruptly, the beds are contorted, and the orientation of the joint system is changed. Beds within the excavated area may be so thin, fractured, or disturbed that quarrying is impracticable.

(3) Folding offers less difficulty to exploitation in thickly bedded than thinly bedded sedimentary rock, because the greater thickness permits a wider range of operations and minimizes the possibility of exhausting the supply. Rock in thick beds is usually more uniform in quality than it is in thinly bedded deposits. Shale, slate, and schist beds are frequently thicker

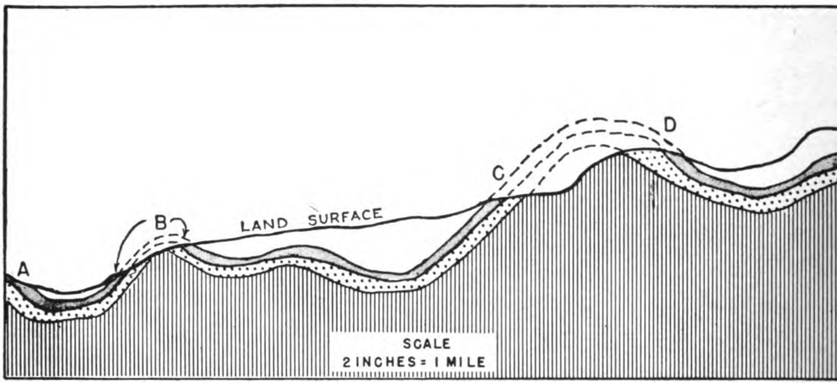



*Figure 170. Repetition of surface exposures of folded beds. Synclinal areas are covered by overburden; anticlinal segments are removed by erosion.*

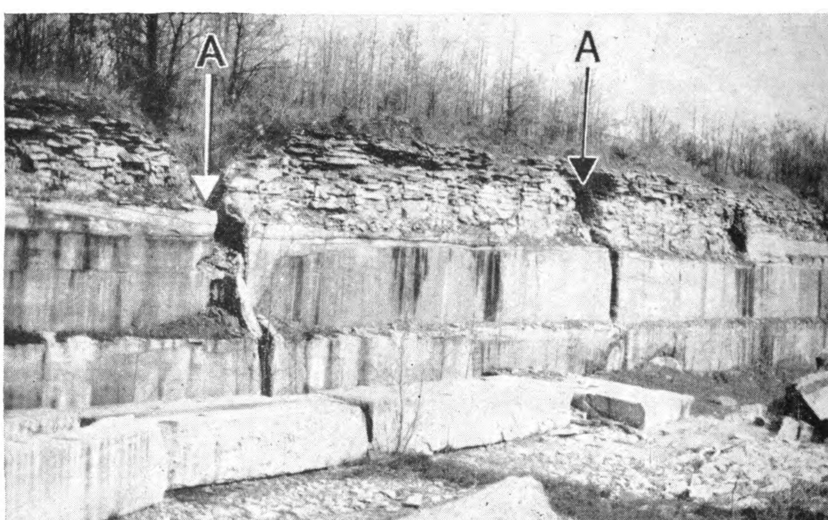



*Figure 171. Thinly bedded, platy limestone underlain by thickly bedded massive limestone. Widening of joints at A and A[1] caused by weathering.*

near he crest of a fold than along the sides. Limestone and marble commonly show some fracturing in folds. Strongly cemented sandstones and quartzite are even more brittle and will be more fractured than limestone and marble under the same conditions of folding.

(4) All sedimentary beds that lie at an angle to the horizontal may be regarded as flanks of either anticlinal or synclinal folds, regardless of the magnitude of the folds. Exposures that might otherwise show this relationship are frequently obscured by erosion of the upper beds at and near the crest of anticlines, by a cover of younger rocks, or by deposition

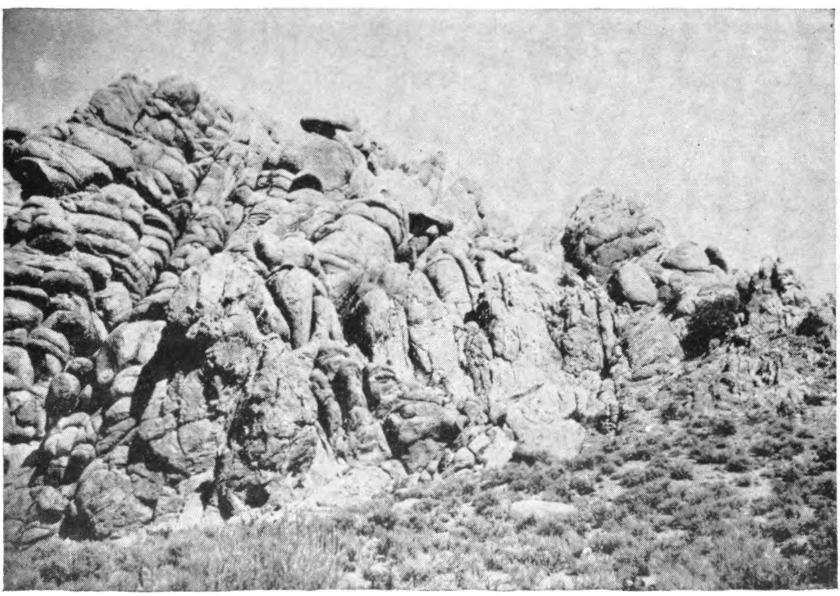


*Figure 172. Joints and fissures in granite widened by chemical and mechanical weathering. Yosemite National Park, California.*

of alluvium in the troughs of synclines. In such areas where folding is complex and concealed by erosion and deposition, a study of the general type of folding often makes it relatively easy to find the continuation of a layer of desirable rock in another part of the area, because of the repetition of the sequence of the beds (fig. 170). This fact may be especially important in the attempt to find additional supplies of material as near as possible to initial operations.

c. *Joints.* Joints facilitate the breaking of massive rock into blocks

and fragments, and much of the art of quarrying lies in taking advantage of natural joints and fracture planes. Recognition of their existence in fresh rock is difficult at times, but in weathered rock it is usually easy due to discoloration and bleaching or widening caused by percolating water. Widening of joints is brought about by either the ready solubility of the rock (fig. 171), or the susceptibility of the rock to chemical and mechanical agents of weathering (fig. 172).

(1) *Igneous rocks.* Jointing in igneous rocks is seldom as regular as in sedimentary rocks. It follows patterns which more or less correspond to those of the sedimentary rocks.

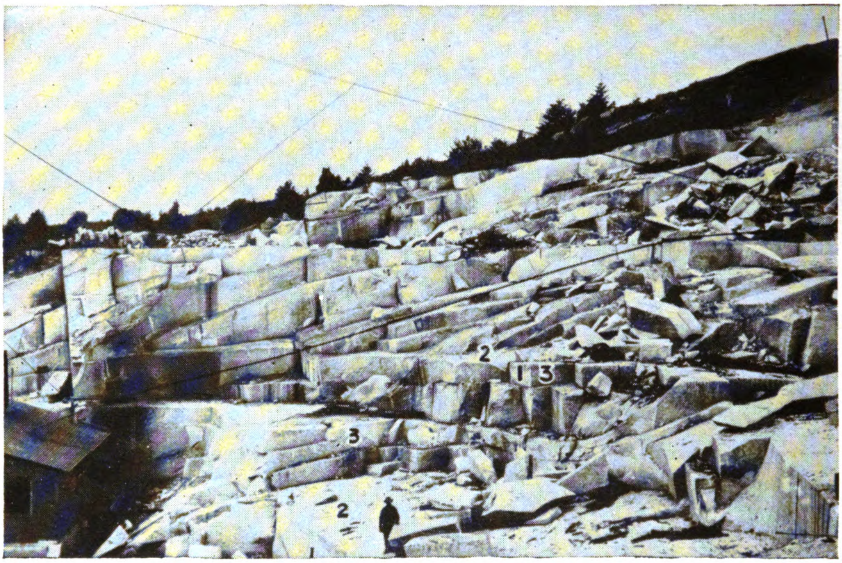



*Figure 173. A Vermont granite quarry. Numbers identify the three separate planes along which the massive granite is split in quarrying operations. Listed in order of ease of splitting they are (1) the rift, (2) the grain, and (3) the head or hardway.*

(*a*) In massive granite, quarrymen take advantage of three directions of separation or jointing: the *rift,* the direction of easiest parting which may be either horizontal or vertical; the *grain,* the next easiest direction of parting; and the *"hardway,"* the direction of more difficult parting in any direction other than rift and grain (fig. 173). Two of these directions of separation are vertical joints accompanied by minor irregular joints. The third direction consists of a set of cross-

*Figure 174. Sheeting in a granite quarry. Stonington, Maine.*

joints which are undulating and merge into each other. These cross-joints, sometimes called *sheeting* or *false-bedding* (fig. 174), are believed to be surface effects, as they occur approximately parallel to the slope of the surface of the ground. The interval between joints usually increase with depth until the joints are no longer apparent. Whenever granite is found with numerous, close vertical joints in the surface beds, it may be inferred that planes of weakness exist in the lower beds even if they cannot be seen.

(*b*) Basalt with symmetrical, well-developed columnar jointing favors quarrying.

(*c*) Trap and most dike rock, with the exception of those deposits of basalt which exhibit columnar jointing, have no direction of regular jointing.

(2) *Metamorphic rocks.* Schist and gneiss have no regular direction of jointing. However, foliation planes or rock fracture planes in some of the metamorphic rocks have about the same effect on ease of quarrying as jointing has in igneous rocks.

(3) *Sedimentary rocks.*

(*a*) In stratified rocks, there are usually two sets of joints

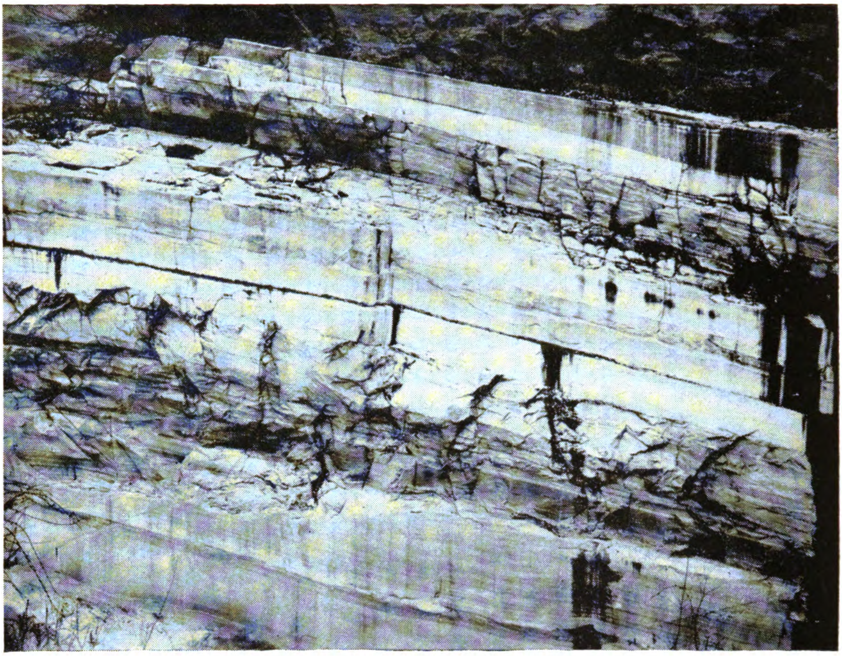


*Figure 175. Jointing in sedimentary rock.*

perpendicular to the planes of bedding, and they often intersect at angles of between 60° and 85°. Joints may die out in a few yards, or may be succeeded by others or merge into them. Parallelism of a series of joints varies from a few feet to a few yards. The width becomes less in thinly bedded rock, promoting easy breakage into small cubes and parallelopipeds. Where stratified rcoks are inclined to the horizontal, the joints in the direction of the strike are usually more pronounced than those in the direction of the dip.

(*b*) The regularity, spacing, and abundance of joints vary from one bed to another in the succession of strata. They may be shifted or interrupted in passing from one bed to another. Some beds are more regularly jointed than others; in fact, jointing in each bed appears to be more or less independent of that in associated beds (fig. 175). Fine-grained limestone and sandstone usually have the most regular and well-defined jointing systems.

*d. Bedding.* Bedding or layering in sedimentary rocks has about the same effect on ease of quarrying as sheeting has in igneous rocks. If the bedding planes are very closely spaced, the stone may be suitable for flagging, paving blocks, light riprap, and rubble masonry; but it will of course, be valueless as dimension stone, heavy riprap, heavy architectural masonry, and engineering masonry, where a considerable block thickness is required.

## 122. Water

Water frequently presents two problems in the working of construction material deposits. One problem is securing a supply for washing and processing the material as required. The other problem, and at times more serious, is the avoidance or removal of water from workings discussed in paragraph 97.

# Section VI. WORKING THE DEPOSIT

## 123. General

*a.* Application of geologic principles to pit and quarry operations will help expedite removal of the material, safeguard personnel and equipment, and prevent disastrous effects on man-made or natural features adjacent to the prospect site.

*b.* The operational procedures dictated by geologic phenomena are discussed in this section. For information on the engineering aspects of pit and quarry operations, see FM 5–10.

## 124. Removal of Material from River Bed

*a.* The type of equipment available for the recovery of river sand and gravel must be considered during prospecting of an area. If the equipment consists only of bulldozers, scrapers, and power shovels, the large bars, banks, and terraces will have to be worked (fig. 158). With draglines and floating suction dredges, the main channel of the river may be the most favorable location.

*b.* When sand and gravel are obtained from the main channel with suction dredges or draglines, there is danger that removal of large quantities may upset the equilibrium of the river bed and thus cause scour around bridge abutments. A study of the depth of moving

river-bed material and of the amount of the movement, however, should give indications of the quantity that can be removed with safety. If the amount of sand and gravel being dredged at any one spot is any appreciable percentage of the material which is on the move, it can only mean that some site further downstream is being starved of supplies and scouring will take place.

## 125. Coral Pits and Quarries

*a.* Coral may be obtained from cuts on the construction site, from quarries, and from wet or dry borrow pits worked in benches. Rooters should be used to loosen the softer deposits and the loosened material should be moved with bulldozers to power shovels for loading into trucks or other transport equipment (fig. 163). Rooting and panning are preferable in soft coral pits or shallow lagoons. Where coral requires little loosening, draglines and carryall scrapers can be used. Occasionally, coral from fringing reefs and lagoons can be dug by draglines or shovels, piled as a causeway, and then trucked away progressively from the seaward end. Hard coral in cuts or aggregate quarries requires considerable blasting. In both pit and quarry operations hard coral "heads" are often found embedded in the softer deposit, presenting a hazard to equipment and requiring blasting.

*b.* Blasting hard coral differs somewhat from ordinary rock quarrying since coral formations contain innumerable fissures in varying directions and many large voids. The porosity of the coral structure itself decreases blasting efficiency. Conventional use of low-percent

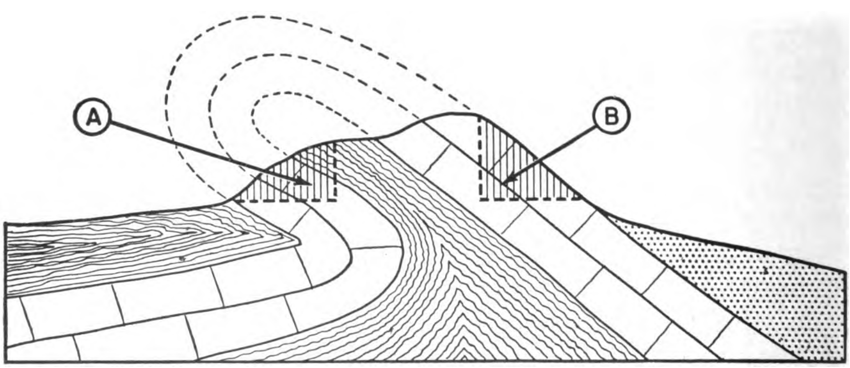



*Figure 176. Jointing in folded strata. For quarrying, site B, where dip is favorable and overburden thin, is preferable to site A where dip would produce overhanging beds.*

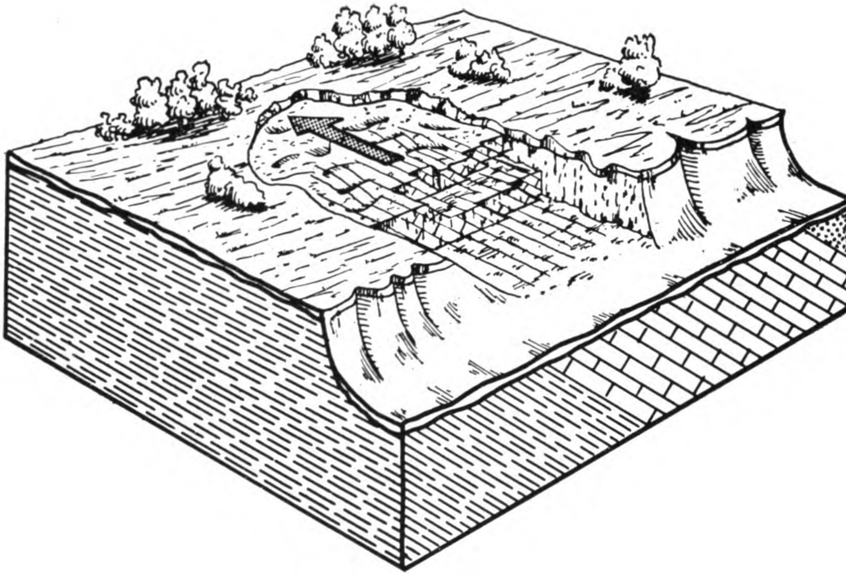


*Figure 177. Quarry operations in inclined strata.*

dynamite in tamped holes produces the most satisfactory results. Shaped charges, especially when used under water, are ineffective; cratering charges, although effective, are uneconomical.

## 126. Quarry Operations in Folded Strata

*a.* In dipping beds of sandstone, marble, and limestone it may be more desirable to work the quarry floor on a slant parallel with the bedding instead of working it horizontally, partly because the incline facilitates the extraction of rectangular blocks.

*b.* When the beds dip into the hill, the overburden will increase with the distance from the outcrop, even though the hill surface itself does not rise (fig. 176). In this case, it may be practicable to quarry by underground chambers (fig. 169).

*c.* If the dip of the beds rises with the hill, the thickness of overburden does not necessarily increase.

*d.* Operations should normally be directed either away from the downfolded side or along the strike of the beds (fig. 177).

## 127. Quarry Operations in Faulted Strata

Excavation and quarry operations in the vicinity of a fault in layered rock should usually proceed parallel with or away from the fault to avoid difficulty.

## 128. Quarry Operations in Jointed Rocks

A quarry face should be parallel or at right angles to the joint planes in order to avoid waste.

# CHAPTER 7

# ROAD LOCATION AND AIRFIELD SITE SELECTION

## Section I. GENERAL CONSIDERATIONS

### 129. Value of Naturally Suitable Sites

*a.* The more suitable the natural conditions are for a road or airfield, the less time and materials are required for construction. After a road or airfield is completed in a suitable terrain, it will need less maintenance or possible reconstruction. In military operations where speed is necessary and men and equipment are limited, it is imperative to select the most favorable natural site which will meet the military requirements.

*b.* The major construction problems at the selected route or site must be anticipated. Before the construction is planned, a careful study of topographic, ground, and subsurface conditions is important even when heavy equipment is available and time is not limited. It is better to spend extra time locating a site which needs a minimum of earth moving than to bulldoze the first convenient site. Bulldozing might have an adverse effect on some soils. For example, some laterite soils, typical of tropical regions, are friable and well-draining in the natural undisturbed state but, on being worked, become plastic and hard to stabilize. Also, grading may lead to the removal of a more stable topsoil or A horizon in some areas, and thus expose a less stable clayey B horizon.

### 130. Factors Affecting the Natural Suitability of Sites

*a.* The factors affecting the suitability of road location and airfield site selection are—

(1) *Topography* (pars. 62–85): extent of flat ground; smoothness and slope of ground; topographic obstacles to airfield approaches.

(2) *Ground:* bearing strength (par. 87); ease of excavation and stabilization; drainability.
(3) *Drainage:* surface drainage; subsurface drainage (par. 92); height of water table.
(4) *Weather:* prevailing wind direction; storms; amount and distribution of precipitation (par. 153*a*(2)).
(5) *Clearing:* vegetation and buildings.
(6) *Access:* existing facilities; ease of access construction.
(7) *Water supply:* availability of surface and ground water (ch. 8).
(8) *Construction materials:* sources of natural (pars. 104–111) and processed materials.

*b.* A geologic evaluation of a site should be based on all the factors given in *a* above, not on a single factor. For example, an evaluation of the topography, which can be accomplished quickly, might show a site to be ideal for an airfield because it has reasonably flat surfaces and favorable approaches. A more thorough study, however, might eliminate the site because of undesirable ground characteristics, poor drainage, and inadequate water supply.

## 131. Procedure for Geologic Evaluation of Factors

*a.* In the preliminary choice of areas most likely to provide good sites, knowledge of the regional geology can be the basis for a general terrain evaluation. For the evaluation of individual sites, large-scale maps and aerial photographs supplmented by ground reconnaissance can provide the basis for estimating ground characteristics, drainage, water supply, and construction materials factors. Close-range study, supplemented by boring and sampling, can sometimes lead to finding superior locations not far from sites which are unsatisfactory in one or more respects. All available information should be acquired that will be helpful for the final selection of the site and for planning the actual construction of the road or airfield.

*b.* The recommended procedure in selecting an airfield site is presented by a hypothetical problem given in section IV below.

## 132. Aids in Selection of Sites

*a. Use of Intelligence Reports in Site Selection.* The airfield site-study map (fig. 178) and site description (fig. 179) provide ready-made geologic interpretations of the best areas suitable for airfield

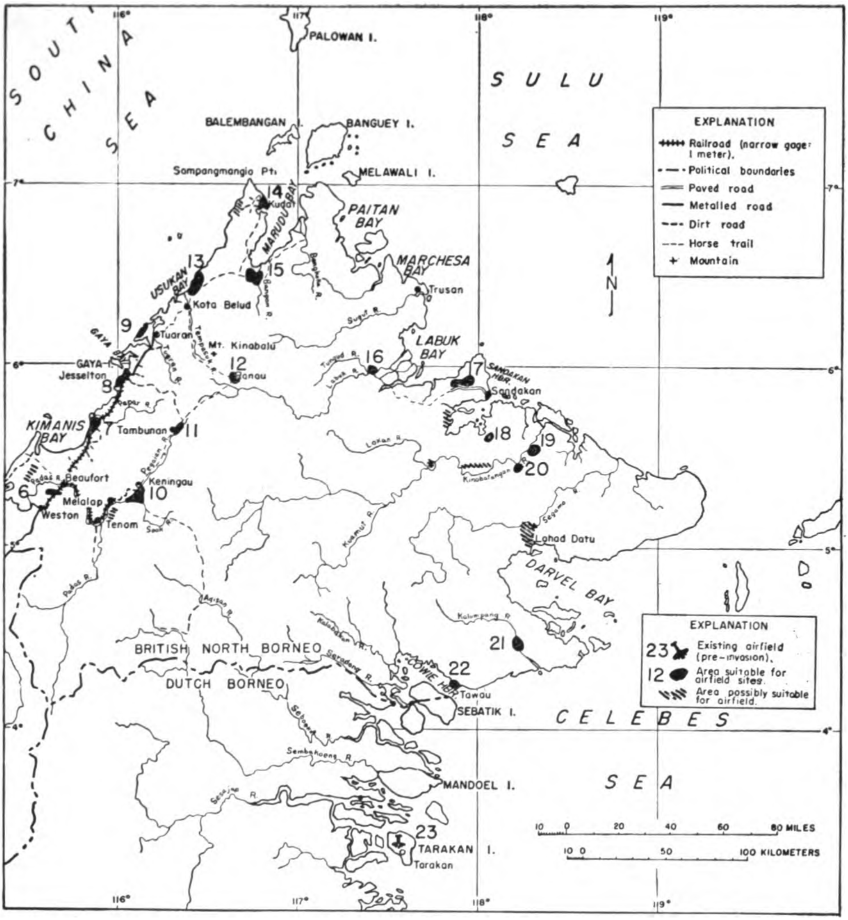


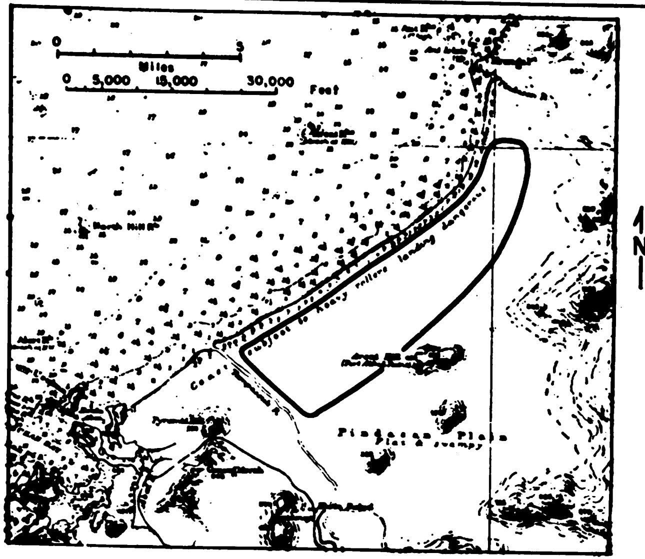

*Figure 178. Airfield site-study map of part of North Borneo.*

sites. When these intelligence reports are available, the engineer is relieved of the problem of area selection and can direct his energy to reconnaissance and close-range study of the site dictated by the military requirements.

*b. Use of Topographic Maps in Site Selection.*

(1) Topographic maps, through geologic inference, may yield considerable information other than topography (par. 55*b*). Their greatest use, however, is in planning road routes and airfield runways. For initial location planning, a map with a scale of 1:50,000 is as small as can be successfully used.

RELIABILITY RATING: CLASS C




Source: H.O. chart 2121, 1910.
Altitudes in feet above sea level.
Depths in fathoms.

AREA 13

**Rating:** Good.

**Location and Accessibility:** Coastal area north of Usukan Bay, about 40 miles NE of Jesselton, and a few miles north of Kota Balud. Access to Marudu Bay area by horse trails and to Jesselton by horse trails and metalled road.

**Topographic Setting:** Flat to undulatory coastal plain about 2½ by 9 miles including some swampy tracts; isolated hills 300 to 1000 feet high at south; higher mountains at east and north. Runways could probably be oriented in any direction. Approaches clear only on seaward side.

**Clearing:** Mostly grass and brush; some forest and swamp vegetation. Bulldozers can handle former, but cutting and possibly blasting required for latter.

**Grading:** Some grading necessary; also filling of swampy spots.

**Foundation Conditions:** Sandy loam, loam, and clay. Addition of aggregate may be necessary to develop good subgrade where soil is clayey. Natural wearing surface fair to good; impervious surfacing desirable.

**Drainage:** Artificial drainage of swampy tracts necessary unless runways can be laid out to avoid them.

**Construction Materials:** Sand available on beach; sand and gravel from bed of Tampasuk River. Also sand, gravel, and clay obtainable by excavation on site. Rock suitable for construction can probably be quarried in bordering hills.

**Water Supply:** Abundant supplies from Tampusak River; will be brackish unless taken above tidal limit. Additional supplies available by digging or drilling shallow wells.

*Figure 179. Example of site description for area in North Borneo.*

For construction planning (detailed work), maps with a scale of 1:5,000 or larger should be used.

(2) Standard topographic maps with a contour interval of 20 feet or more are undesirable because they tend to show sharp irregularities as smooth elements and, in a region of low relief, give only a generalized view of the land surface. Such maps may not show some important features such as ravines, low escarpments, rock knobs, and sinkholes. For this reason, when a potential site has been selected, detailed topographic maps with a contour interval of 5 feet or less should be used. If the areas are inaccessible to ground parties, such maps can be made from clear stereoscopic aerial photographs, although lack of ground control reduces the accuracy of the maps.

*c. Use of Geologic Maps and Reports in Site Selection.*

(1) Geologic maps and reports may be among the most useful sources of basic information in the selection of roadway locations and airfield sites. In either, however, interpretation is necessary if the geologic units and terminology are to be converted into information which can be applied to the engineer's needs (par. 54).

(2) Geologic maps are useful for the primary narrowing of large land areas into units more and less likely to contain good sites, particularly if the map is made on a topographic base. The nature of the landscape can be ascertained; and generalizations can be made as to the texture and drainage of the subgrades, and whether the foundation will be directly on the rock mapped, on soils derived from the rock, or on transported soils. Some of the interpretations that can be made from geologic maps are as follows:

(*a*) Areas in which alluvium is of substantial thickness are indicated on all geologic maps. This provides a means of identifying alluvial valley and coastal and interior plains. The older alluvium (Pleistocene) is usually differentiated on the maps from the recent alluvium (Recent).

(*b*) Plateaus and high-level plains can be identified by the distribution pattern of flat-laying rock. The hard, stratified rocks, such as sandstone and limestone, and volcanic extrusives such as basalt, serve as cap rock of individual plateau segments.

(*c*) In regions where loess, sand dunes, glacial till, or other unconsolidated deposits cover the bedrock, special surficial geologic maps (par. 54*d*) are sometimes available showing the distribution of these deposits.

(*d*) Erosional surfaces in the uplands (peneplain surfaces) can usually be identified when a geologic map is made on a topographic base. Such surfaces are usually described in geologic reports.

(3) Geologic maps help locate construction materials (pars. 86–101) and sources of ground water for road and airfield construction (pars. 148–187).

*d. Use of Soil Maps and Reports in Site Selection.* If soil maps and reports (par. 55*a*) are available in addition to geologic maps, they can be used to amplify the details of foundation interpretation, for several soils having important characteristic differences may be present on one geologic formation.

*e. Use of Aerial Photographs in Site Selection.*

(1) Aerial photographs are valuable in the study of proposed and existing airfield sites, especially when the site cannot be reached. They are most useful and reliable when they are used to supplement and refine other information, or when used in conjunction with ground investigation (figs. 180 and 181.)

(2) When interpreting surface soil and rock conditions from aerial photographs, the following items are considered:

(*a*) *The basic geologic land form* establishes the dominant parent material in the area and in many cases the type, attitude, and character of the bedrock.

(*b*) *The degree of the prevailing soil slopes* reflects the cohesive quality of the soil which is related to the clay content.

(*c*) *The pattern of surface drainage* is a reflection of both the topography or structure (par. 27*b*(2)) and the soil type.

(*d*) *The results of erosion* partially reflect the sand and silt content of the soil and the degree of soil drainage.

(*e*) *Variation in soil color on black and white prints* provides a partial key to soil moisture content, the darker areas having the higher moisture content.

INDEX MAP-OKINAWA

| NUMBER AND MAP SYMBOL | |
|---|---|
| 1. | Silt and |
| 2. | Clay & |
| 3. | Clay loa |
| 4. | Clay loa base of |
| 5. | Sandy l |
| 6. | Clay & of sandy |
| 7. | Clay lo |
| 8. | Gravelly |

(*f*) *Vegetative cover.* The type and amount of vegetation partially reflect the soil type and the degree of soil moisture present.

(*g*) *Land use.* This indicates to some degree the soil type and the quantity of moisture available in the soils, based on the kind of crops raised and the presence or absence of irrigation facilities.

(3) The items listed in (2)(*a*) through (*g*) above are discussed in detail in Civil Aeronautics Administration Technical Development Report No. 52, The Origin, Distribution, and Airphoto Identification of United States Soils.

## Section II. EVALUATION OF TERRAIN TYPES AS ROAD AND AIRFIELD SITES

### 133. General

*a.* Because roads and airfields are similar, the general principles of location and site selection normally apply to both. Roads, however, are not as dependent on good site selection as are airfields. Roads can be constructed to follow topographic irregularities, but airfields must be constructed on level or nearly level ground where cut and fill operations can be kept at a minimum. Also, roads are not so limited by the character of the surface and subsurface materials over which they are constructed as are airfields.

*b.* Each general type of terrain, the alluvial plain, the terrace, the bedrock plain, the hill and mountain, contains certain geologic elements which are common to that type of terrain wherever it is encountered. Because these elements have similar geologic origins, it is possible to predict to some extent what surface and subsurface conditions will be associated with each type. This section analyzes the suitability of the general terrain types with regard to road location and airfield site selection.

### 134. Alluvial Valleys and Coastal and Interior Alluvial Plains

*a. Topography and Soils.*

(1) Alluvial valleys and coastal and interior alluvial plains are the sites of a majority of the world's airfields. These plains contain extensive flat lands, have few prominences which can

restrict approaches, and require little or no grading. When grading is required, the ground is usually soft and easily excavated.

(2) Differences in the manner of deposition and the source of the alluvial material may cause the soils of the plains areas to vary widely in type and characteristics from place to place. The more suitable areas, having better drainage and coarser soil, can be expected at the margins of plains where alluvial fans spread out from the foot of bordering hills and mountains. Such areas are also found along streams which are bordered by natural levees, and along the coast on dunes and sandy beach ridges.

(3) Some plains areas are typically poorly drained and are underlain by fine, silty, or clayey soils. Such soils are hard to stabilize and may be subject to heaving during freezing weather. The water table is generally high and flooding possibilities should always be considered. Obviously, swamps, bogs, and marshes are to be avoided if possible. They are poorly drained and are usually underlain by both fine-grained and organic soils. These soils are characteristically difficult to stabilize, often involving an expense of time and labor not feasible in many military operations.

*b. Availability of Construction Materials.* Streams and beaches may be sources of sand and gravel if suitable nearby rock has provided source material to the streams or waves. Usually, river gravel is most abundant in stream beds close to hills or mountains of hard rock, but is practically nonexistent in deltas at the outer edges of wide plains. Beaches on coral islands are composed largely of coral sand, not of common quartz sand which is usually lacking.

*c. Availability of Water.* Except in arid regions, water is usually obtainable from nearby streams or lakes. Ground water is also usually obtainable without difficulty.

## 135. Alluvial Fans

Large alluvial fans are generally ideal road or airfield sites as they commonly have well-drained, gently sloping surfaces, and sandy to gravelly soil (fig. 182). Adjacent high land and diversion dikes may restrict approaches to airfields from some directions. Ditches may be necessary to protect sites from flash floods which may be accompanied by mud flows (par. 25).

*Figure 182. Airfield sited on an alluvial fan. Furnace Creek, Death Valley, California.*

## 136. Natural Levees

When no other more suitable locations exist, the natural levees of large streams may provide acceptable road and airfield sites, except where flood conditions are prevalent or extensive. The soil materials of levees are composed of coarser materials and are normally better drained than are those of the lower land on the adjoining floodplain. The sand composing the levees may be too fine and silty to have high bearing power, although it is usually better in this respect than is the soil of the surrounding area. Alinement of highways and runways would necessarily be limited to the direction of elongation of the levees and fill might be required to widen the levee. Fill is not practicable

where streams are actively cutting into their banks, except for temporary installations.

## 137. Alluvial and Marine Terraces

*a. Topography and Soils.*

(1) The flat benches or terraces, which in places border alluvial plains, continental coastlines, or islands, can sometimes provide excellent sites for road or airfield construction (fig. 183). Their flat surfaces are above the adjacent stream, lake, or ocean levels, so they are generally well-drained and free from the danger of floods. In alluvial terraces, the water table is normally low and drainage is generally easy to establish where natural drainage is not sufficient.
Depth of bedrock varies with the type of terrace (pars. 27 and 47).

(2) The main objection to terraces as road and airfield sites is the frequent presence of steep-walled valleys and ravines, which occasionally are so closely spaced that they cut the

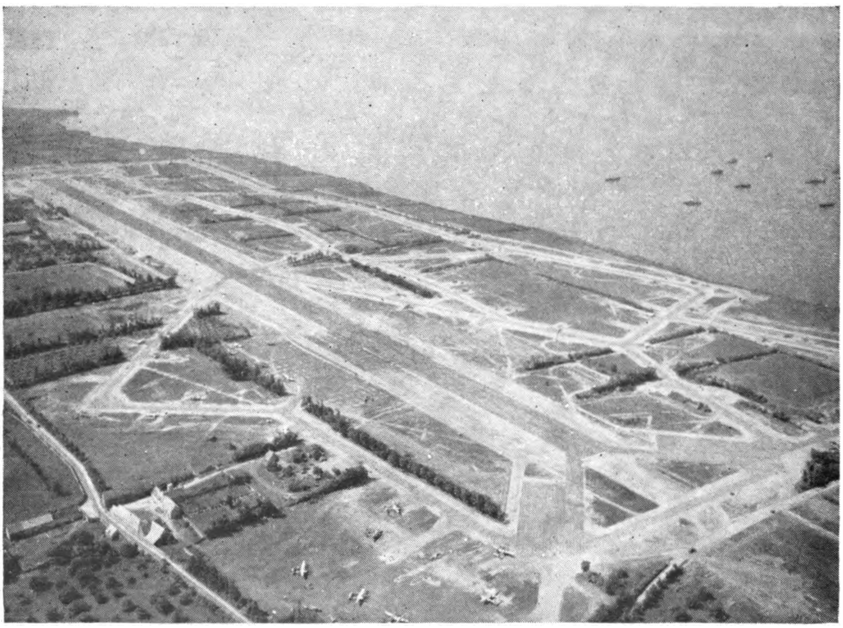


*Figure 183. Airfield sited on a well-drained marine terrace. France.*

surface into small segments. Also, an escarpment close to the end of the airfields' clear zone is a psychological hazard. It may also produce dangerous air currents.

*b. Availability of Construction Materials.* Gravel and sand deposits suitable for use as construction material underlie many terraces and are usually obtainable from bordering escarpments or ravine walls. Hard rock also may be exposed in cuts or in nearby hills and mountains.

*c. Availability of Water.* See paragraphs 148–187.

## 138. Bedrock Plains and Plateaus

*a. Topography and Soils.*

(1) High-level plains or plateaus, underlain by flat-lying rocks or developed by erosion on folded or massive rocks, may be acceptable locations for airfields in areas where more suitable alluvial locations are lacking. In rugged volcanic areas, such as the Kurile Island chain, small plateaus formed by lava flows may provide the only relatively level land of any considerable extent (fig. 184). In places, rock plateaus may be superior to adjacent lowlands as road or airfield sites, especially where the lowlands are poorly drained or offer poor foundations.

(2) The flat plateau surfaces may be intricately dissected by ravines. In addition, some surfaces may contain minor relief irregularities, such as the scabland type of topography on lava plateaus and the sinkholes and pinnacles on some limestone-capped plateaus. In such cases, grading generally requires rock excavation. The high surfaces are naturally well-drained or, if not, good drainage can be easily established. Foundations are generally good.

(3) The residual soil cover on bedrock plains may vary considerably in thickness and character, depending on the underlying rocks, the age and geologic history of the plateau, and climatic conditions. In places, as on recent lava flows, the residual soil may be very thin or entirely lacking. In other places, particularly in the tropics, the mantle may be so thick that grading does not reach bedrock and the finished foundation is on the soft, residual material. The bedrock under plateaus and high plains may also be covered by thick deposits of transported materials, such as falls of ash or coarser

*Figure 184. Airfield sited on lava plain.*

fragments ejected from volcanoes, loess, dune sand, stream-distributed gravel and sand, and glacial drift. Such foundations vary greatly as to suitability. Some consist of well-drained, coarse soils, such as the fragmental igneous rock soils and sand dunes, and the sandy, residual soils developed

on granites. Other foundations have poorly drained, fine soils, such as the clayey soils developed in place on rocks like limestone and shale, and the plastic, clayey soils (gumbotil) found in some areas of glacial drift. Loess and other silty materials, when undrained because of underlying impervious beds, may be subject to frost heave.

*b. Availability of Construction Materials.* Rock suitable for construction is usually abundant on bedrock plains and plateaus, and sand and gravel are locally available.

*c. Availability of Water.* The distribution and amount of supplies of surface and ground water available are highly irregular.

## 139. Hills and Mountains

The rough terrain of hills and mountains makes them generally unsuitable for both roads and airfields, although roads can, and often must be constructed in this type of terrain. Where necessary, airstrips could be located in valley bottoms or on level uplands within the hilly or mountainous area. Such level areas occur on the tops of ridges and hills, and sometimes along the slopes, as remnants of a former plateau or erosional surface which has been dissected. Because the level uplands are generally very limited in size, construction usually involves much excavation of hard rock. Lengths and orientations of runways and roads are drastically limited, both in valleys and on the uplands. Access is difficult and water supply may be inadequate.

# Section III. CLIMACTIC MODIFICATIONS

## 140. General

Climate materially affects the natural conditions existing at or near the earth's surface. In arid, tropical, arctic, or subarctic climates a given terrain type might differ from the same type in a temperate climate as to suitability for road and airfield sites. This section covers generalized climatic modifications.

## 141. Arid Regions

In arid regions the dry, barren plains permit construction of roads and airfields with a minimum of effort. For foundations, the soil, except where completely loose and drifting, is naturally firm or easily

stabilized. The firm, gravelly desert pavement (par. 30*b*) is often an ideal natural foundation. Drainage is not a factor, but dust and the scarcity of water are problems. A dust palliative is generally required. Dry lake bottoms provided highly satisfactory airfield sites in Tunisia during World War II.

## 142. Humid, Tropical Regions

In humid tropical regions, the plains are usually very wet and thickly overgrown. The water table is high and the soil is clayey, with a hardpan usually present. The locating of areas with better-drained ground, such as beach ridges, is particularly important in the tropics. The identification of natural vegetation or crops that distinguish the drier ground is valuable for site reconnaissance. Except on the most recently deposited rocks, such as some lava flows and reef limestones, deep residual soils are developed and firm rock is scarce. Laterite (par. 22*b*), and reef limestone (par. 28*c*(4)) are two types of materials characteristic of the tropics. They are readily available and easily worked. If properly handled, they usually make good foundations or surfacing material, although certain laterites have proved to be poor surfacing material. Experience in the use of a particular laterite is necessary when utilizing the material for road or airfield construction.

## 143. Arctic and Subarctic Regions

In arctic and subarctic regions wet ground and permafrost are major problems. Rarely are large areas underlain by homogeneous, well-drained, coarse, nonheaving soils. Differential heaving and settling are caused by differences in soil texture, the irregular distribution of permafrost, and the varying thawing effects which construction has on the permafrost (fig. 144). As a result, runways, pavement, and structures warp. The impervious frozen layer close to the ground surface creates difficult drainage problems and, when thawed, may permit flooding of a site by ground water from an unfrozen horizon above the permafrost. Detailed study should be made of the permafrost conditions so roads and runways can be located in the most favorable site available and the proper precautions taken in construction (fig. 185). In general, construction precautions involve maintaining the thermal balance of the ground as much as possible and laying a thick base course of coarse, nonheaving, and free-draining sand or gravel. See also paragraphs 93 and 94.

*Figure 185. Northway Airfield. Eastern Alaska.*

## Section IV. HYPOTHETICAL PROBLEM SHOWING PROCEDURE IN SELECTING AN AIRFIELD SITE

### 144. Problem

An airfield is to be constructed in a little-developed area. A study of maps and aerial photographs indicates the presence of a high terrace and a coastal plain, both topographically suitable for airfield construction. Inland, the whole area is surrounded by hills with rather steep slopes. The problem is to select the best locations for runways and other facilities; to select the best routes for the necessary access roads; to determine the nature of the subgrade and its drainage; and to determine the kind of pavement best suited for the airfield. After these decisions are made, the next step is to locate the sources of the best materials for constructing the pavement and the other facilities. The amounts of materials available must be estimated. Methods of obtaining adequate supplies of water for drinking and construction must also be determined.

### 145. Field Reconnaissance

A survey of the flat areas on the high terrace and in the coastal plain is conducted by surface inspection, soil sampling, and subsurface

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drilling. Rapid reconnaissance may narrow down the number of possible areas by eliminating sections subject to floods, as shown by stream habit, high-water marks, and topographic position. It may also eliminate areas with obviously poor drainage or low bearing power, as indicated by position, land use, and surface soil texture. A few borings may be made in the reconnaissance stage, but a trained man can cover large areas rapidly by inspecting only the surface, ravine sides, and road cuts.

## 146. Evaluation of Reconnaissance Data

A study based on the field reconnaissance finds that only the terrace area is actually suited to airfield construction. The coastal plain is found to be composed of flat-lying, silty material with a high organic content. Also, the elevation of the plateau is too low to permit effective drainage. Without effective drainage, the soil cannot be compacted sufficiently to support the required loads. The remaining alternative, an extremely thick base course, is not economically justified since a satisfactory alternative site is nearby.

## 147. Detailed Study of Site Selected

*a. Geologic History.* The terrace originated as an uplifted coastal plain, composed of material laid down by a large river which flowed from the hills. The gradient of the river decreased as it left the hills. The deposited material formed an alluvial fan, over which the river now flows in an irregular, braided channel.

*b. Lithology.* The surface of the terrace consists of sandy silt. The surface is underlain by bedded silt and clay with some lenses and stringers of sand and gravel. The clay is fairly well-compacted by nature and has low shrinkage and expansion coefficients.

*c. Surface and Subsurface Water.* The water table is a considerable distance below the surface, although a few perched water zones are present in the sand and gravel lenses. The surface is easily drained by ditches, since the land has a gentle slope and most of the ditches would reach the gravel stringers which are water carriers.

*d. Building Sites.* Closer to the hills, the sloping portion of the terrace, which originated as an alluvial fan, is found to be an ideal site for such buildings as barracks and hangars, because it is well-drained and has a gravelly soil with high bearing power. This area is also a satisfactory source of fill material and contains some gravelly

sand suitable for use as aggregate. Other supplies of gravel are available in the streambeds.

*e. Access Roads.* The problem of locating an access road through the surrounding hills is also solved in part by geologic interpretation. The hills are found to consist of a mixture of flat-bedded shale and massive, hard sandstone. Knowledge of this fact is extremely important, since there are great differences between the two beds as to subgrade conditions present. Other construction problems are radically different in the areas underlain by the two kinds of rocks. Shallow sandy soil over the sandstone means that a satisfactory foundation can be obtained but that the grading would be difficult and costly. The shale, on the other hand, is easily graded but its overlying soil is clayey, poorly drained, and subject to landslide in wet weather. The geologic finding is that the most economical procedure is to locate the road on the most level parts of the sandstone areas and to avoid both level and steeply sloping areas over the shale. In the shale areas, provision is made to insure free drainage, and the likelihood of landslides is decreased by the location of ditches so as to prevent the subsoil from becoming saturated with water.

*f. Construction Material.* The sandstone is found to be a good source of hard rock which, when crushed, is well-suited for use as aggregate and base-course material. Blasting is needed to loosen it, but little or no drilling will be needed and the best results will be obtained if advantage is taken of the regular distribution of cracks and joints in the rocks.

# CHAPTER 8

# GEOLOGY OF WATER SUPPLY

## Section I. GENERAL

### 148. General

Knowledge of the earth's topography and of the characteristics of geologic formations helps the engineer find and evaluate supplies of water. Some sources of supply, such as streams, lakes, and springs, are easy to find, because they are on the surface of the earth. Other sources are below the surface and at times require much searching before they can be found. The application of geologic principles can help eliminate areas where no large supply is present beneath the surface and can indicate areas in which the search should be concentrated. Evaluation of both surface and subsurface supplies benefits from the knowledge of geologic principles which control the occurrence of water and of the characteristics of the earth which indicate pollution, salinity, and other qualitative features.

### 149. Sources of Supply

*a. Surface Water.* Streams and lakes are the most available and commonly used sources for military water supply, especially when the water must be obtained quickly, as during combat operations.

*b. Springs.* Springs are easily found and developed. They are not common in most regions, however, and the majority are too small to be of much value when a large water supply is needed.

*c. Ground Water.* Most land is underlain by one or more rock formations that will yield at least small perennial supplies of water to wells. In areas where good aquifers are present, wells may be the best source of supply for both temporary and permanent bases. Wells are better than streams in that their yield is more dependable, the quality of the water is better, and their location is more flexible. Sometimes, however, the quantity may be too small to justify attempts at recovery, or the water may be too mineralized to use. Sometimes, too, the time required to sink wells makes them less preferable than immediately available surface sources.

## 150. Characteristics of the Supply

Paragraphs 153, 154, and 172–177 discuss the sources of supply and the characteristics of the specific terrain types in regard to water supply. In surface water and springs (pars. 153–158), the principal factors to be considered are the adequacy of the source to supply the needs of the troops (dependability of flow) and the quality of the water. In subsurface water (pars. 159–171), the persistency and the productivity of the water-bearing horizons are more important considerations than dependability of flow or quality of water, although, in some areas, the intrusion of salt water is an important factor influencing the quality of water (pars. 172–177). The flow is relatively persistent if the well is bottomed in the permanently saturated zone, and the quality of water is generally good although the mineralization is occasionally present. In paragraphs 159–177, where possible, the most desirable well points are indicated. In some terrains, however, an aquifer may persist over large areas so that any otherwise desirable location is an acceptable site for a well.

## 151. Finding the Supply

Paragraphs 178–182 discuss maps, reports, and miscellaneous criteria which are aids in finding a ground-water supply. The most important of the miscellaneous criteria is plants. Some species are good indicators of the depth of water and are useful, therefore, in finding relatively shallow sources of ground-water supply.

## 152. Field Reconnaissance

Paragraphs 183–187 discuss the general aspects of a geologic field reconnaissance as applied to a ground-water survey. The section includes preparations for making the reconnaissance, selection of equipment and type of reconnaissance, the field observations to be made and the data to be recorded, and, finally, the utilization of the data collected in the prediction of ground-water supplies.

# Section II. SURFACE WATER

## 153. Streams

Streams that are largely fed by ground water are much better sources of water supply than those fed mainly by surface runoff. The flow

is relatively constant and dependable, and the water is usually clear. Streams fed mainly by direct surface runoff are less desirable because they may fail during droughts; at high stages they tend to be excessively muddy; and the quality of their water may fluctuate so much and so quickly that purification is difficult. Most streams, being fed by both ground water and surface runoff, are intermediate between these two extremes.

*a. Dependability of Flow.* For the initial phase of field operations, the surface-water supply source need merely be adequate at the time of the year for which the operation is planned. It is often expedient to use an available stream source, even though it may require considerable treatment to be drinkable and may go dry during drought periods. For large long-term supplies, however, the minimum flow during drought periods and the quality of water must be considered in selecting a source. The criteria given in (1) through (4) below will usually be applied only in selecting sources of supply for semipermanent or permanent bases. Before a ground examination is made, the available intelligence data on surface-water resources of the area and the best topographic maps and aerial photographs should be studied.

(1) *Discharge records.* Discharge records are available for most of the large streams in the United States and in Europe. These records provide the surest way of knowing the safe annual yield of a stream—the amount of water it will supply even during droughts. For large areas of the earth, however, no records or only fragmentary records are available. In addition, stream measurements generally are made only of the larger streams of a region, even in the United States and other countries where intensive stream gaging has been done (fig. 186). For many smaller streams that are possible sources of water supply there are usually no records for long periods. For some streams without records, the regimen (year-round flow characteristics) can be estimated from the flow records of nearby streams. Even where there are no discharge records for any stream in the region, it is possible for an experienced hydrologist to make a good estimate of the stream regimen. This is done by evaluating all of the factors that influence runoff and ground-water storage.

(2) *Precipitation records* (fig. 187, 188 and 189). Precipitation records indicate the water available in an area. In the absence of adequate precipitation records, aerial photographs

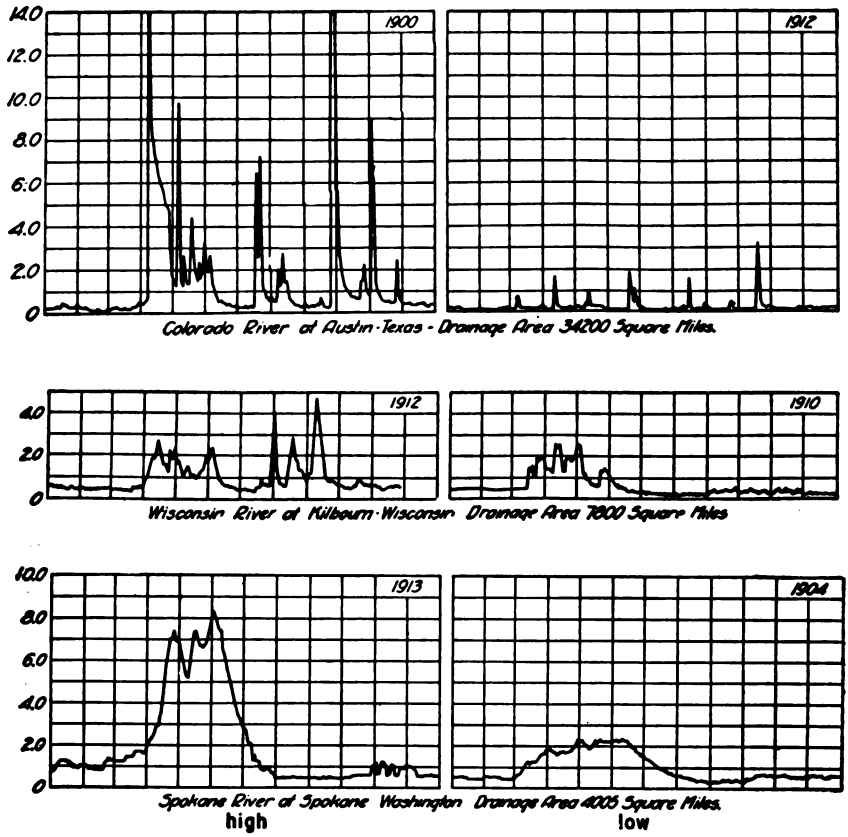


*Figure 186. Hydrographs of typical streams for years of high flow and low flow. Vertical scale: cubic feet per second per square mile of drainage area. Horizontal scale: months.*

can be studied to gain an idea of the severity and frequency of droughts and their effect on stream flow, by noting whether or not the predominant vegetation species are drought-resistant. Generalizations on the year-round flow of streams which can be made on the basis of annual precipitation records are:

(*a*) In temperate and tropical regions having less than 25 inches of annual precipitation (as is the case in more than 30 percent of the land surface of the earth), most streams are intermittent. Here the rate of evaporation equals or exceeds the average rate of precipitation, and runoff is

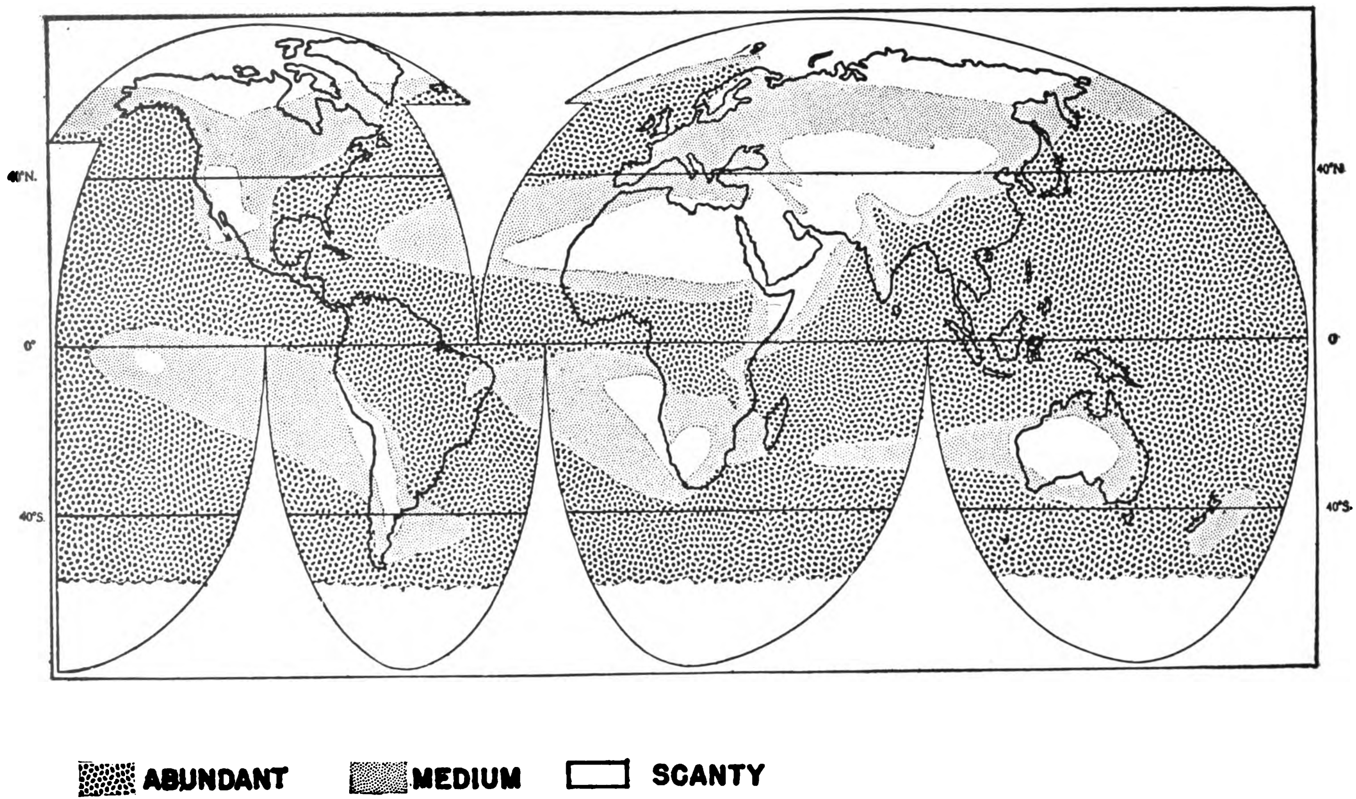


*Figure 187. Map showing distribution of rainfall throughout the world.*

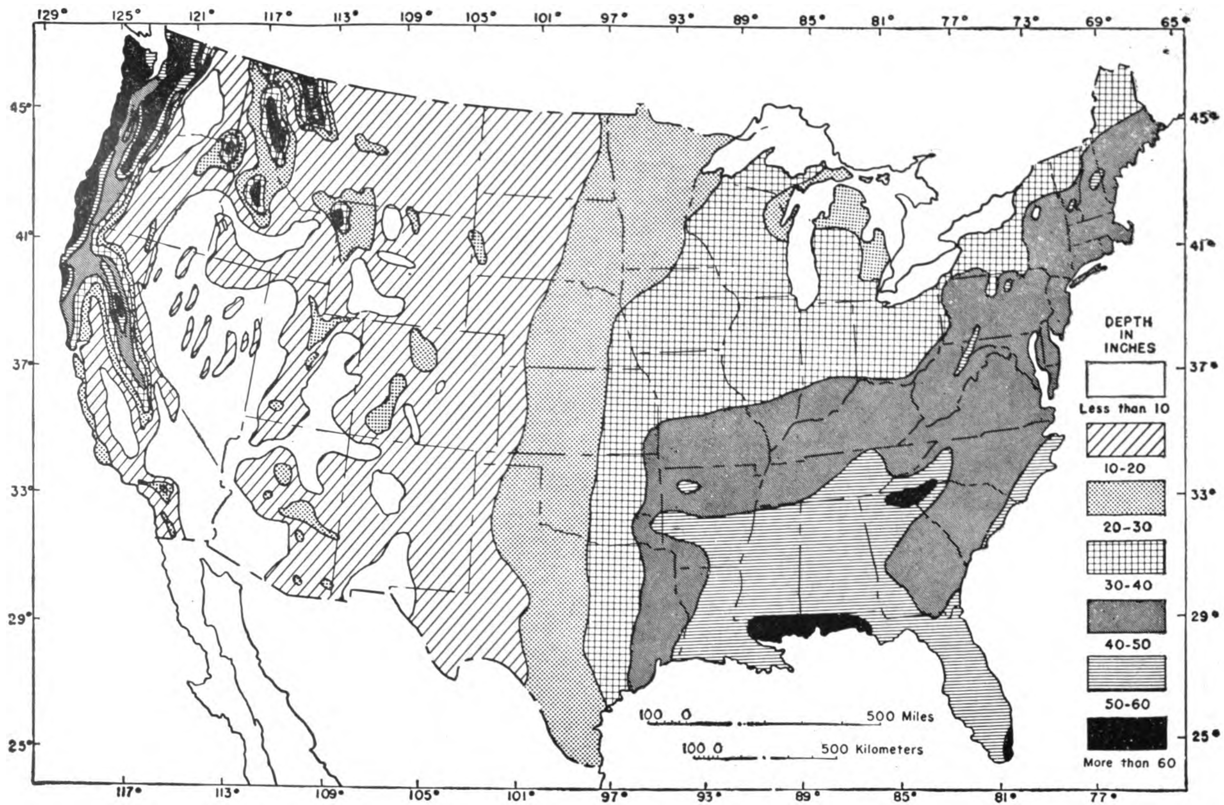


Figure 188. Map of the United States showing mean annual precipitation.

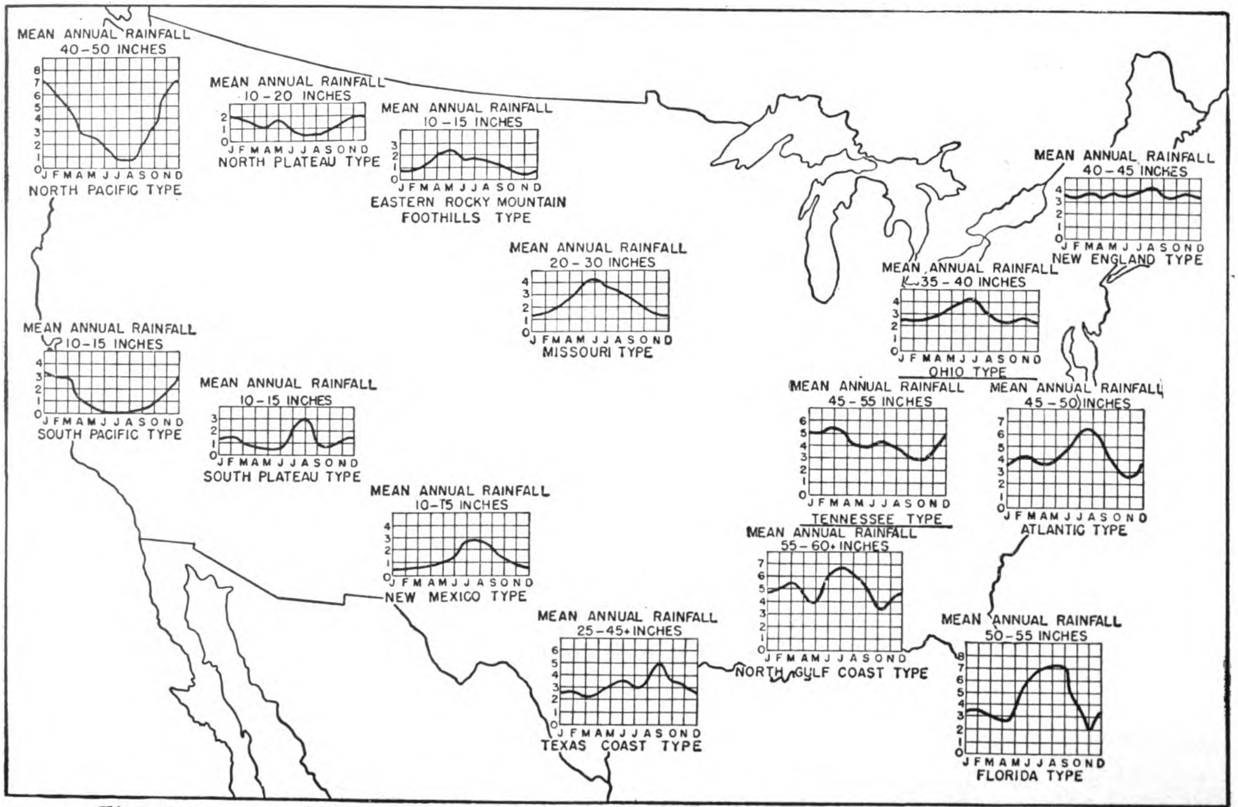


*Figure 189.* *Distribution of monthly precipitation in different regions of the United States.*
(By permission from: "Climates of the United States," Ward, R. de C. Copyright 1925. Harvard University Press.)

largely incidental, depending on the intensity of rainfall during a given period. When rainfall is light, all the water may evaporate and there will be no runoff. On the other hand, heavy rains may cause severe floods, because the vegetation will be too sparse to retard the runoff appreciably.

(*b*) In temperate regions having more than 25 inches of annual precipitation and in tropical regions having more than 35 or 40 inches, most of the streams flow most of the year, the number increasing with the annual precipitation and with the evenness of the seasonal distribution of rainfall.

(3) *Field examination during wet seasons.* A field examination of streams during the wet season should search for the following features, which indicate permanency of flow:

(*a*) A major stream channel deep with respect to its width, instead of a wide belt of interconnecting shallow channels.

(*b*) Relatively fine material in the stream bottom, consisting of gravel and sand rather than large boulders, very fine material along the banks of floodplains, mostly silt with a small proportion of sand and no cobbles or boulders. Floodplains with well-developed soil horizons suggest that widespread overflow are very rare (where flooding is frequent, soil horizons have little opportunity to develop).

(*c*) A moderate to sluggish current in plains or lowland areas where unconsolidated deposits compose the stream bottom. Current in hard-rock gorge areas is of no particular significance.

(*d*) Water-loving vegetation along stream banks (fig. 190); for example, in the western United States such trees as willow, cottonwood, and tamerisk (salt cedar). If the floodplain, as well as the banks, has a dense cover of plants demanding moderate to high year-round water supplies, the probability of year-round flow is strengthened.

(*e*) Stream temperature which is warm in cold weather (warmer than average air temperature) and cold in warm weather strongly suggesting ground-water feeding which will continue through the dry season.

(*f*) Water which never gets very muddy, indicating that much of the flow comes from ground-water seepage or springs and will likely continue throughout the year. Very muddy

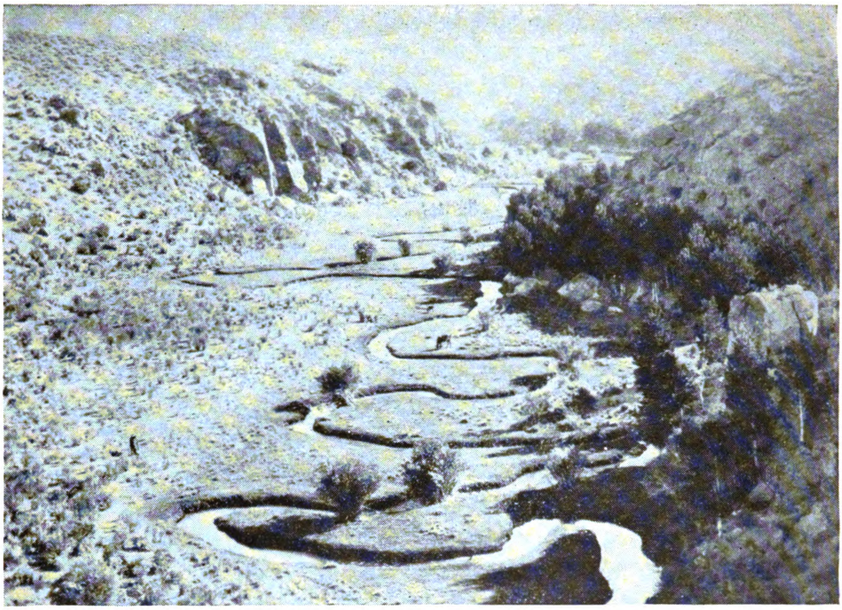

*Figure 190. A meandering stream with more or less constant flow as indicated by grass-covered floodplain. Crooked Creek, California.*

streams suggest poor vegetation cover at the source, as well as rapid runoff, resulting in reduced ground-water feeding during the dry season.

(4) *Field examination during dry seasons.* The dry season is the best time to observe a stream's minimum water-supply potentialities. At this time, however, it is more difficult to be certain that the location of water points will be beyond the range of severe floods. Indicators of possible flood conditions are soil horizons ((3)(*b*) above), high-water marks, such as leaves, twigs, and driftwood caught in bushes or trees above bank height of streams, and water stains on buildings, trees, ledges, or other objects above bank height of streams.

*b. Quality of Water.* Surface water is never chemically pure. It always contains some sediment, bacteria, or dissolved matter. If any of these impurities are present in great quantities, the water may be unfit for drinking and other uses.

(1) *Pollution.* Streams in inhabited regions are particularly apt to be polluted with harmful bacteria, the most dangerous

kind of impurity in water. This is true not only in countries where sanitation is poor but also in the United States and Europe where many towns located on the rivers pass raw sewage into the streams. In other countries, such as Korea, surface-water sources are likely to be highly polluted because of the use of human excrement as fertilizer.

(2) *Turbidity.* Streams are apt to be muddy when surface runoff predominates, particularly during flood stages and when their flow is flashy. If the stream channel or floodplain shows evidence of flooding or if the climate is hot and arid, the stream is likely to be muddy, at least at high stages. Streams with uniform flow tend to be clear. Lake-fed or mainly spring-fed streams not only will be clear, but will have less variation in quality than streams fed mainly by surface runoff.

(3) *Dissolved salts.* Surface water usually contains such small amounts of dissolved salts that its chemical quality is not in question for ordinary uses. Locally, however, this factor may need to be considered, especially along seacoasts where invasion of sea water is likely and in arid regions where some streams and lakes may be saline. If marked salinity is in evidence at high or ordinary stages, it will certainly increase at low stages. Tidal effects should be considered in streams along seacoasts, for at high tide the salt water commonly extends farther inland than at low tide. In the tropics, mangroves and nipa palms are infallible indicators of salt water. Mangroves (fig. 191) grow only where the water is usually very salty and covers their roots at high tide; nipa palms (fig. 192) grow in the zone of brackish water farther inland. In temperate regions, indicators are the grasses and other plants that grow only on saline soil or in the shallow brackish or salt water that is present in tidal marshes or along salt lakes and streams.

## 154. Lakes

*a. Dependability of Flow.*

(1) Most lakes are excellent sources for water supply. Even small lakes are good sources, for they have relatively large amounts of stored water for immediate supply and are much more constant in the quantity of available water than the streams that feed them. For supplying large installations,

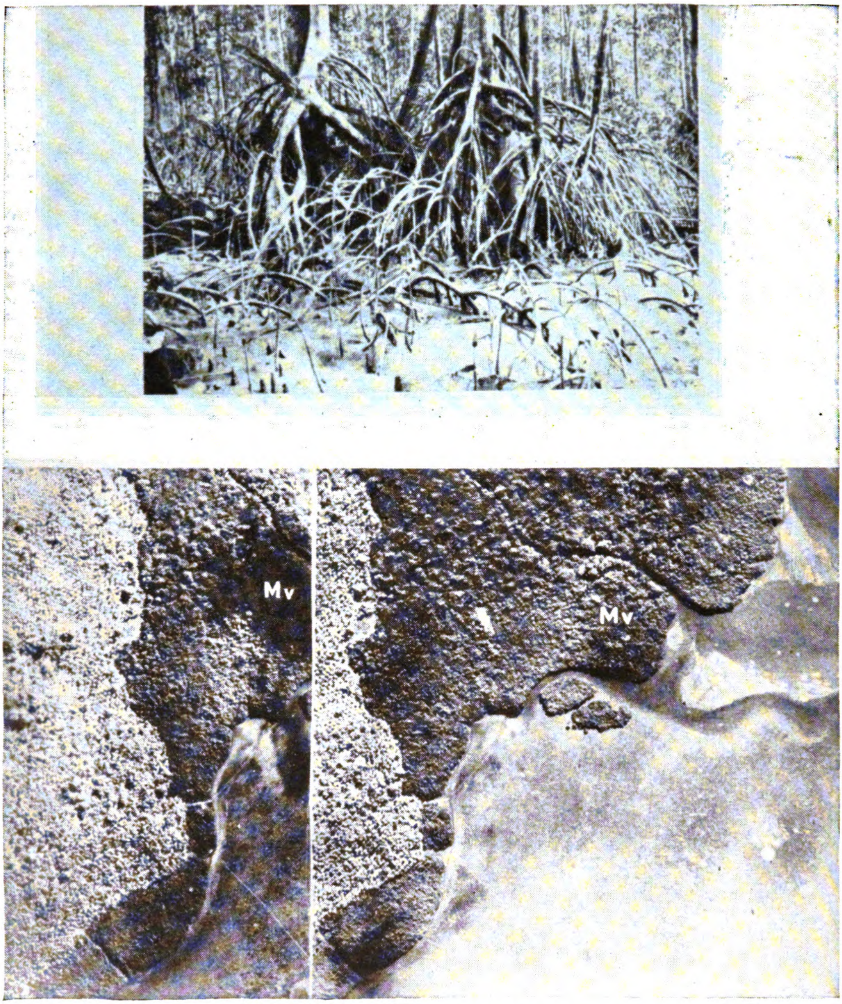


*Figure 191. Views of mangrove swamps. Upper, ground view, Malay Peninsula. Lower, aerial view of mangrove (MV) on Ponape.*

from small lakes, it is well to study the inflow (streams or springs) if there is a possibility that the year-round yield may become critically low.

(2) In humid regions, the lakes are fresh and practically all are permanent. Most of them have outlets which regulate the maximum size of the lake. Unless the rainfall is very

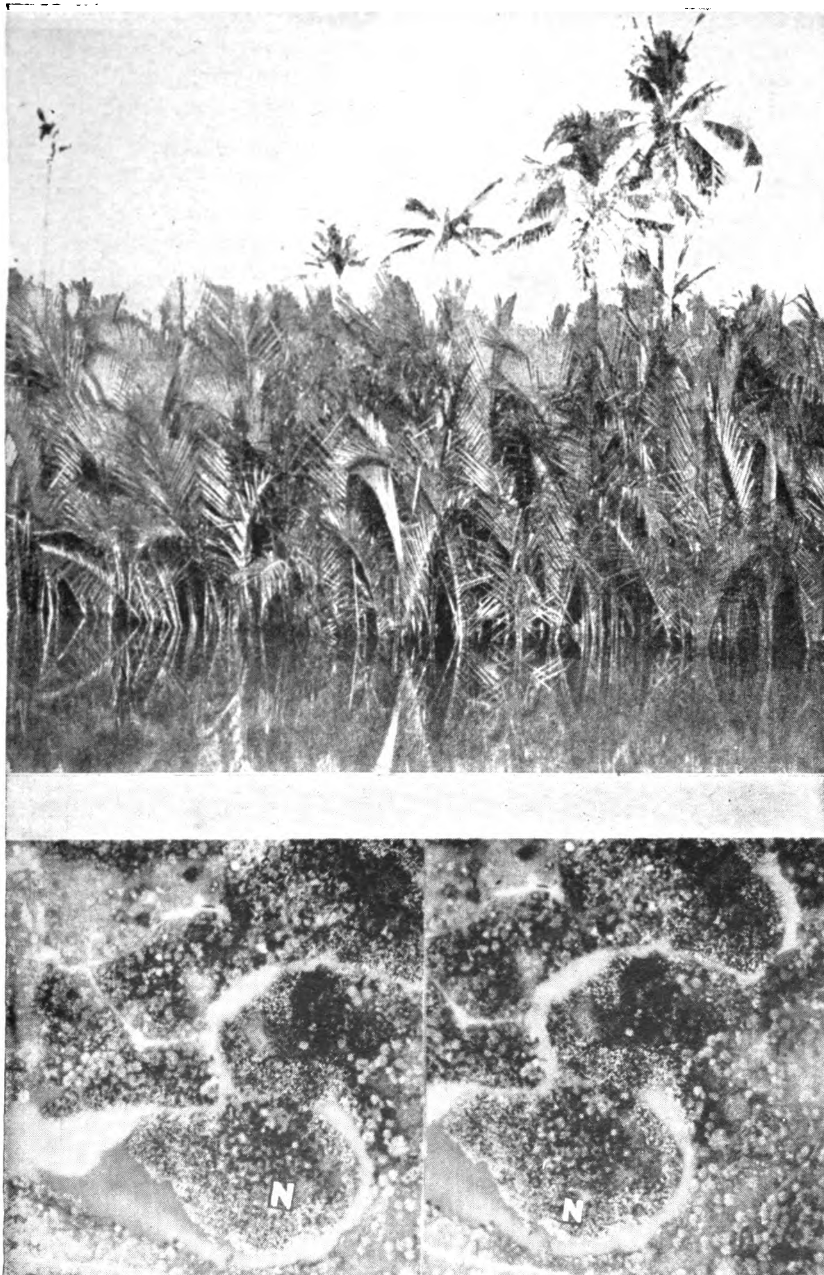


***Figure 192.*** *Views of nipa palms, northern New Guinea. Upper ground view. Lower, aerial view of nipa palms (N).*

erratic, most of the lakes do not change greatly in size from season to season or from year to year.

(3) In most large lowland deserts, lakes are extremely rare or entirely lacking. Where mountains alternate with intervening desert basins, many of the basins have lakes. Unfortunately, however, many of these are temporary or are so salty that they cannot be used for water supply.

(4) In the tundra regions of the Arctic, drainage is poor and lakes are very numerous, and as a rule, though unpalatable, they are excellent water-supply sources. Shallow lakes may freeze to the bottom in winter.

*b. Quality of Water.* Generally the water in lakes is of excellent quality. Large lakes are preferable; usually, the larger the lake, the purer the water. Very shallow lakes and small ponds are more likely to be polluted, and they contain aquatic vegetation, such as algae, and other microscopic plants, that commonly give the water a foul taste and smell. The purity of water improves as the distance from shore increases. If a lake is big enough, the sediment from even the muddiest streams will settle out and any sewage dumped into the lake near the shore will not affect the purity of the water in the interior of the lake. In small lakes the purifying effect is only partial, and the water may require sterilization to be safe for drinking.

## Section III. SPRINGS

### 155. Seeps

*a.* Seeps are quite common. They often show merely as marshy places on slopes or at the base of slopes and may dry up during droughts. In arid climates no water shows at the surface, because it is used up by water-loving plants. These plants indicate the presence of ground water near the surface.

*b.* Many seeps can be made to supply water by collecting and concentrating their flow by means of pits, trenches, drains, and galleries.

### 156. Gravity Springs

*a. Dependability of Flow.*

(1) The yield of all gravity springs is likely to fluctuate as the level of the water rises and falls. Many gravity springs en-

tirely cease flowing after droughts of several months. This is most likely to happen where the water table fluctuates many feet, as is common in regions with pronounced wet and dry seasons and where the soil or rock from which the springs issue is not very permeable. Because of the slowness of ground-water movement, there may be a lag of several weeks or months in the effect of rainy or dry periods on the flow of gravity springs. The flow of springs fluctuates much less, however, than that of streams in the same region.

(2) Most gravity springs issue from material that is only moderately pervious and usually yield less than 5 gallons a minute. Where good aquifers crop out, large springs may issue. Some springs issuing from pervious sandstone, conglomerate, cavernous limestones, or lava beds yield several hundred or, more rarely, several thousand gallons a minute. Practically all the very large springs issue from cavernous limestones or lava beds (fig. 201).

*b. Quality of Water.*

(1) *Pollution.* Gravity springs may be polluted. In many cases pollution occurs when, or after, the water issues from the ground. In other cases the ground water that feeds the spring may itself be polluted from such things as cesspools and leaky sewers situated upslope from the spring. Most soils and rocks are such effective filters that there is little danger of pollution from relatively distant sources; for example, more than 2000 feet away or a much shorter distance in sand or finer-grained materials. In limestones and some types of lava rock having large fissures, however, there may be little filtering action and pollution can be carried long distances. Water from limestone springs, therefore, should be purified with the same care as surface water.

(2) *Mineralization.* Like any ground-water source, spring water commonly is somewhat more mineralized than the local surface water. Although the water usually is soft in areas of granite, schist, or shale rocks, it may be quite hard in limestone, sandstone, or volcanic rock country. Springs that contain unusual amounts of mineral substance in solution or perceptible amounts of unusual minerals, are called *mineral springs.*

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## 157. Artesian Springs

*a. Dependability of Flow.* Artesian springs are practically constant and most yield water that is warmer than the shallow ground water.

*b. Quality of Water.* Artesian springs are likely to be more heavily mineralized than ordinary springs; in many cases the water is unpalatable or even undrinkable. They are generally free from pollution if the outlet is properly protected.

## 158. General Precautions for Development of Springs

Special precaution should be used in blasting to increase spring yield or to construct basins. Blasting in unconsolidated rocks may shift sand or gravel in such a way as to divert the spring flow to a different point. In unconsolidated materials, digging usually is more economical. In hard rocks, blasting may open new fractures which divert water entirely away from the spring or may create fractures in the underlying impervious rock, thus draining the water from the aquifer at that point. Another precaution is to cover all ditches, basins, and outlets to and from the basin to prevent surface contamination and to retard evaporation. Pipes should be used to conduct the water from the basin to the point of use. Nearby surface sources of contamination should be investigated and eliminated if the spring water is to be used for drinking.

# Section IV. GROUND WATER IN AREAS OF UNCONSOLIDATED MATERIAL

## 159. General

*a.* Ground water is most readily available in areas underlain by unconsolidated and poorly consolidated sediments. This is largely because uncemented or only slightly cemented and compacted materials have maximum pore space. These sediments have all been deposited in relatively recent geologic time and are generally restricted to lowland terrain features, such as alluvial valleys, terraces along rivers, alluvial fans, glacial outwash plains, alluvial basins which lie between mountains, and coastwise terraces.

*b.* Three factors having an important bearing on the yield of ground water in unconsolidated sediments are size of particles, cleanness, and degree of sorting or gradation. Clay yields almost no water at all;

silt yields some very slowly. A well-sorted, clean, coarse sand or gravel, on the other hand, yields its water freely. As a rule, deposits of sand are cleaner than deposits of gravel. Clayey sand and clayey gravel can be as impermeable as pure clay.

## 160. Alluvial Valleys

*a. Distribution and Nature of Deposits.* Alluvial valleys or lowlands underlain by stream-laid deposits are widely distributed. They are such distinctive features that they can readily be recognized from geologic maps, topographic maps, and aerial photographs, as well as from the ground. Many geologic maps, however, show only the larger alluvial lowlands of a region. Most geologic reports have such a generalized description of the alluvial materials that they give few clues to the water-bearing properties.

*b. Productivity and Persistency of Water-Bearing Horizons.*

(1) Alluvial valleys are among the most productive terrains for the recovery of ground water except in those areas where no gravel-forming rocks are exposed in the drainage basin. If the surrounding hills are only soft rocks, such as shale, slate, schist, or volcanic ash, they will break down quickly to clay and silt, and will form alluvium which is largely lacking in sand and gravel and is a poor water-bearer. Normally, however, sand and gravel form a large part of the stream alluvium (fig. 193), so that wells located practically anywhere in the alluvium are likely to tap a good aquifer or series of aquifers. Individual aquifers do not usually persist far and the number and depth of water-bearing sands and gravels change rapidly from place to place.

(2) Some parts of an alluvial area may be much better than others. The best type of alluvium is that deposited by year-round streams draining hilly or mountainous country where much resistant hard rock, such as granite or quartzite, is exposed. Under such conditions, the streams carry large amounts of gravel and coarse sand. The stream gradient is so steep that the current washes away much of the silt and clay, and the alluvium may contain many excellent aquifers of clean gravel and sand. In very rugged areas, however, stream gradients may be so steep that the alluvium contains many boulders which cause difficulties in the sinking of wells.

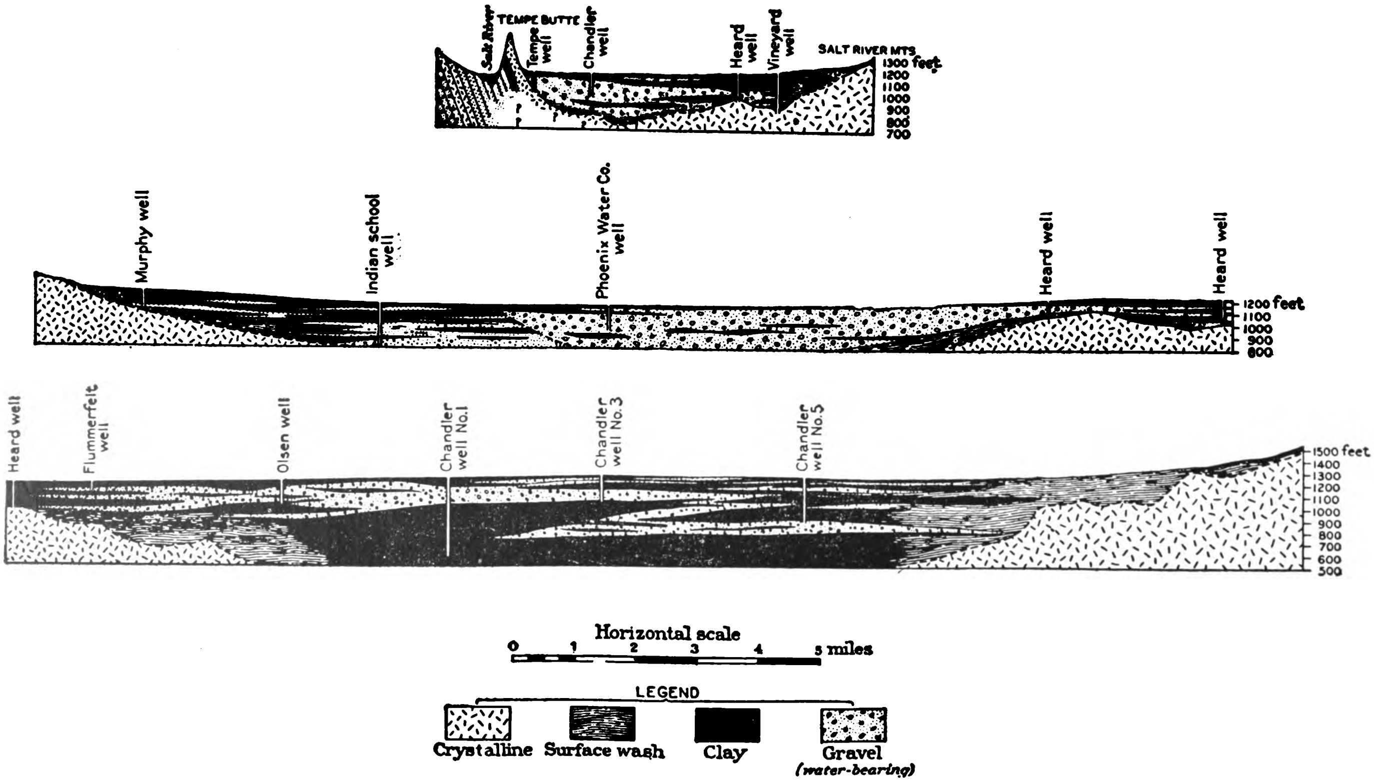



*Figure 193. Alluvium in an arid region, showing variation in valley-fill deposits.*

Alluvium laid down by the erratic and intermittent streams of arid regions is typically less well-sorted, with fewer beds of clean sand and gravel, than that laid down by year-round streams.

(3) Alluvium tends to become progressively finer downstream, as the stream gradient decreases, and as the distance from outcrops of hard rock increases. In the lower courses of streams far from hard-rock highlands, the current may be too sluggish to transport the coarser sediment, and here the alluvium is mostly silt and clay with only a few erratically distributed stringers of sand. A shallow well has a small chance of striking such a sand stringer. Moreover, the sands may be so fine-grained that most wells will have only small or moderate yields, rarely exceeding 50 gallons per minute. For large supplies, several wells may be needed and considerable test drilling done to locate the best aquifers.

*c. Siting of Wells.* The best places for siting shallow wells are the banks of main river channels, where sand stringers are likely to be most numerous at shallow depth. Commonly these banks are natural levees, slightly elevated above the surrounding floodplain and made up of alluvium somewhat sandier than that farther from the channel. If the alluvial deposits are thick, which is the case for many river deltas, deep wells have a better chance of striking a fair or good aquifer, or of intercepting several aquifers and thus obtaining a larger total yield. There is a chance, however, that the deeper aquifers may be saline. Moreover, on some river deltas the alluvial deposits are quite thin. This is the case, for example, in the deltas of several large rivers in south China, such as those of the Chu-kian (Canton or Pearl) and Si-kiang (West), south of Canton, where the alluvium is only 10 to 50 feet thick in many places.

*d. Climatic Influence.*

(1) In the humid tropics, where rocks weather rapidly, clayey soils develop and blanket much of the bedrock. This clay cover makes the alluvium of the tropics generally far less favorable for water supply than that of temperate climates.

(2) In arid regions, intermittent streams may have considerable reservoirs of ground water in their gravel beds. This ground water, flowing in the gravel beneath the stream channel, is called *underflow*. Not all intermittent streams have year-round underflow. The chance of tapping a year-round

underflow is best where the stream alluvium is underlain by impervious bedrock; otherwise, the underflow may sink to a lower body of ground water that can be reached only by deep drilling. Even under year-round streams, gravels do not always contain an underflow. Where the bottom of the actual channel occupied by a stream is rendered impervious by deposition of silts, clay, or mica, its underflow may be at considerable depth, separated from the surface flow by a thickness of dry, though permeable, gravels. Some glacial streams of Alaska exhibit this phenomenon. Underflow of a stream may be forced to the surface where the stream channel is sharply constructed between ledges of impervious rock.

## 161. Stream and Coastal Terraces

Stream and coastal terraces usually are underlain by gravelly or sandy deposits similar to floodplain alluvium. If the terraces are fairly broad and the deposits sufficiently thick, as is the case in most of the coastal terraces, they may be good water-bearers. In some places, terraces are so deeply trenched by stream erosion that practically all the ground water drains rapidly out of the terrace gravel.

## 162. Alluvial Fans

*a. Distribution and Nature of Deposits.* Topographic conditions favorable for the development of alluvial fans can be found in regions where steep mountain slopes rise abruptly from adjacent plains. The streams emerging from the mountains drop the coarsest material near the apex of the fan, and progressively finer material down the slope. At the toe of a large fan, the deposits usually are mostly silt and clay with few stringers of sand.

*b. Productivity and Persistency of Water-Bearing Horizons.*

(1) Alluvial fans are often very productive of ground water, although the depth of water commonly is greater than it is in ordinary alluvial valleys. The aquifers often have a braided pattern and individual beds are very limited in extent. They are most numerous near the mountains, but the depth to water may be great, normally from a hundred to several hundred feet. Down the slope of a fan, the aquifers gradually pinch out. In the lower part of a large fan, test drilling may be needed to locate a productive bed. Small fans with

steep slopes and thin alluvium may yield only small amounts of ground water, but large fans with gentle slopes and thick alluvium may yield large supplies. Commonly, the deeper aquifers will produce hydrostatic pressure in wells in the lower part of the fan. Springs may occur in the lower part of large fans.

(2) Just as with alluvial valleys, the probable yield in alluvial fans can be predicted before drilling, by noting the character of the rocks in the adjacent mountains from which the debris orginated. Shale, marl, soft shaly sandstone, or fine-grained volcanic ash will not produce gravel. Slate or hard limestone may form fairly good gravel, but it is likely to be somewhat cemented. Granite and gneiss generally yield good gravel, especially in arid climates, and quartzite is the best gravel-former of all rocks.

c. *Climatic Influence.*

(1) In arid regions, much of the coarse sediment of an alluvial fan is too poorly sorted to be a good water bearer, but usually there are some stringers of clean gravel or sand that will yield water. The deep fill of many alluvial fans fail to yield much water, probably because of the disintegration and ultimate compaction of the rock particles.

(2) In humid regions, the alluvial valley or basin in which the fans are developed would be the better source of ground water supply.

## 163. Alluvial Basins

a. *Distribution and Nature of Deposit.* Alluvial basins are widely distributed throughout the western portion of the United States, developing in regions where mountains alternate with structural troughs (fig. 194). Waste from the mountains partly fills the basins with alluvium laid down as a series of coalescing alluvial fans. The upper alluvial slopes form *piedmont plains* or *alluvial aprons* that gradually decrease in slope toward the interior of the basin until they merge with the interior flats (fig. 195). Lakes or playas occupying part of the central flat are usually saline, some of them strongly so. Generally, the lake-bottom deposits are largely clay.

b. *Productivity and Persistency of Water-Bearing Horizons.*

(1) Many alluvial basins are extremely productive of ground water, such as those in California and in the Basin-and-Range

Province of Nevada (fig. 196) and neighboring states. They supply large amounts of water for irrigation and for municipal supplies. Good wells commonly yield several hundred to a thousand or more gallons per minute.

(2) In the transition zone between the coarse, gravelly marginal deposits and the lake beds, the aquifers are fairly numerous yet the depth to water is usually not great. The water generally is fresh, and in the deeper aquifers it is often under hydrostatic pressure. When deep wells are drilled in such deposits, the yield of a well will increase progressively as the well is deepened to tap each successive aquifer, and generally the water in each deeper aquifer is under progressively greater pressure (fig. 195).

(3) The few shallow aquifers underlying the lake plains are likely to have water so mineralized with salt, soda, or other compounds that it is unpalatable or undrinkable.

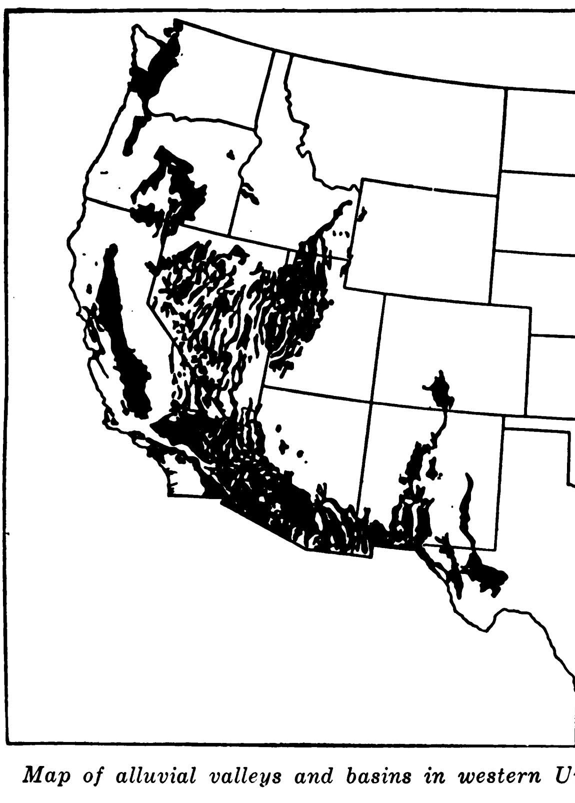


*Figure 194. Map of alluvial valleys and basins in western United States.*

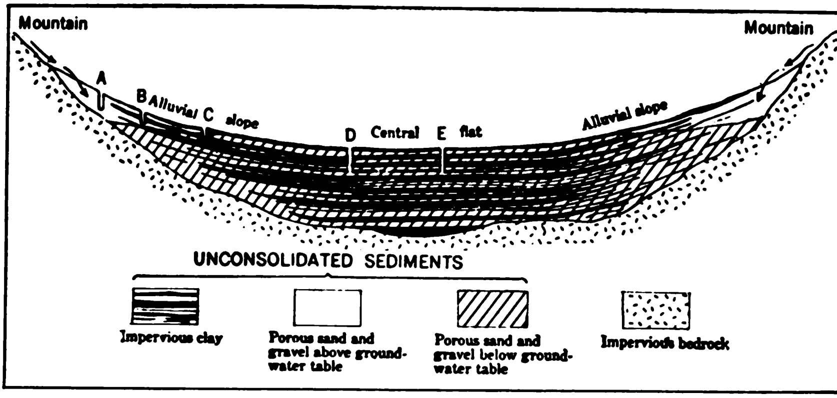



*Figure 195. Diagrammatic cross section of the ground-water conditions in an alluvial basin. A, dry hole. B, dry hole which, if deeper would reach water. C, pumped well. D and E, flowing wells.*

*c. Siting of Wells.* The best place to develop ground water in a basin lying between mountains is in the transition zone between the coarse, gravelly marginal deposits and the lake beds.

## 164. Glacial-Outwash Plains

Vast quantities of alluvium laid down by streams emerging from glaciers contain a higher percentage of gravel and coarse sand than clay and, therefore, are usually very productive of ground water. Extensive deposits occur in all the glaciated regions of the earth, especially in the northern United States, northern Europe, and areas bordering many high mountains. Many sizable cities, including many of those in the upper Mississippi basin, obtain their water from glacial-outwash sediments.

## 165. Till-Covered Plains and Hills

Deposits of glacial till ordinarily are poor water bearers, yielding barely enough for farm wells. In places, outwash sands and gravels are interbedded or associated with the till, forming good aquifers, some of which may carry water under hydrostatic pressure.

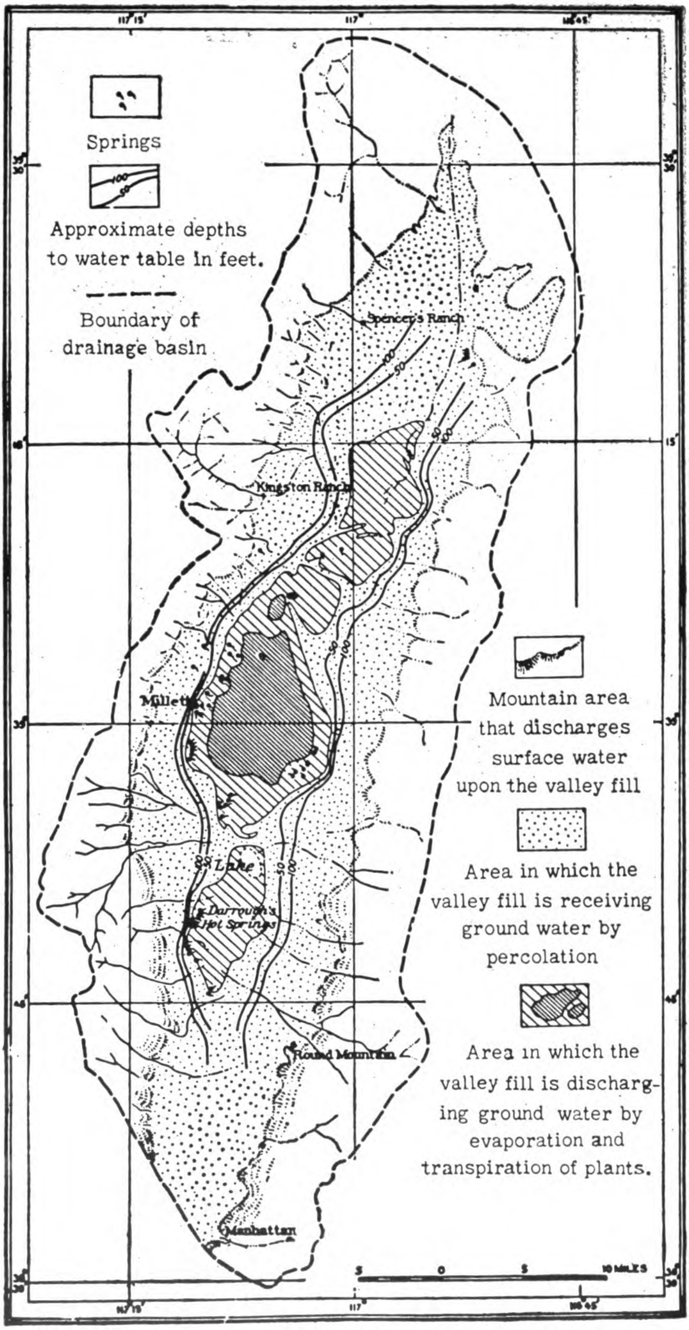



*Figure 196. Occurrence and circulation of ground water in valley fill. Big Smokey Valley, Nevada.*

## Section V. GROUND WATER IN AREAS OF CONSOLIDATED MATERIAL

### 166. General

*a.* Although generally less productive of ground water than unconsolidated-sediment areas, consolidated-sediment areas may have fair, good, or even excellent aquifers. Normally, the most productive hard rocks are sandstone, limestone, and certain volcanic rocks, especially basalt. A consolidated-sediment area generally is more complex structurally, and the distribution, depth, and yield of aquifers may be intimately controlled by the rock structure.

*b.* As in the case of unconsolidated granular sediments the permeability of consolidated sediments, such as sandstone, conglomerate, and limestone, is governed mainly by the grain size and the degree of sorting or gradation. The degree of compaction and cementation is also important. For this reason, conglomerate and sandstone normally yield less water than clean gravel and sand. A good well in sandstone may yield several hundred gallons per minute. Compaction and cementation tend to be more complete the greater the age of the rock. Sandstone, for instance, when it has been deeply buried or has been subjected to high pressures, often becomes quartzite with practically no pore space. Generalizations should not be made, however, because geological processes have acted so differently in various regions that rocks of the same type and age may differ a great deal in permeability.

*c.* Hard rocks other than granular sedimentary rocks, also differ from unconsolidated sediments in their water-bearing properties. The hard rocks are able to transmit water through fractures or other secondary openings produced long after the rock was formed. Unconsolidated sediments are too soft to form open fractures. The more compact a rock is, the more likely it is to develop such fractures. One reason clay is the poorest water bearer of all material is that it not only is unable to transmit water between the grains, but it is too soft to have open fractures. Compact, dry shale, on the other hand, may have joints which yield a little water. Slate and schist are even more likely to have fractures and may be slightly better water bearers, in spite of being so consolidated that the rock itself has almost no porosity. Well-fractured quartzite is even better and, in some localities, wells in this material yield from a hundred to several hundred gallons per minute.

*d.* For a fractured rock to yield water, the fractures must be relatively open. In deeply buried rocks there are few open fractures; most are just beginning to open or are tightly closed. Rock weathering tends to open fractures. In the weathered zone, many otherwise impervious rocks like granite, schist, and slate may have fractures giving small yields within 50 to 100 feet of the surface. Rock fractures produce less if they are filled with clay. This sometimes happens when rocks are in an advanced stage of weathering, and also where earth movements have forced rock masses against one another to form clay seams or gouge pockets between the walls of the fractures. In a formation where water is transmitted only along fractures, the success of a well depends on the number and size of the fractures it encounters and the extent to which these fractures persist and intersect with others. Success in penetrating pervious fractures with a well is largely a matter of chance, but sometimes the chances for success can be increased by a careful study of the fracture systems where the rocks are exposed.

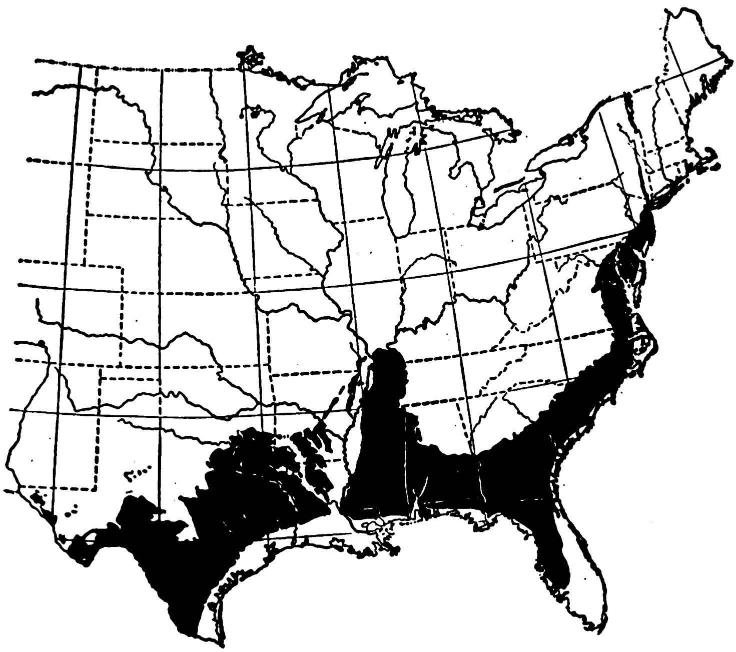


*Figure 197. Map of the Atlantic and Gulf Coastal Plains showing areas where aquifers are numerous.*

## 167. Coastal Plains

*a. Distribution and Nature of Deposits.* The coastal plains which border the continents range from a very narrow strip to a belt many miles wide (fig. 197). They are underlain by poorly consolidated sediments that dip gently toward the sea (fig. 198). Their sediments are deposited predominantly in the sea or at the shore and, in contrast to alluvial sediments, are generally much better sorted and more evenly stratified. Individual beds usually extend for considerable distances laterally and usually have few local irregularities.

*b. Productivity and Persistency of Water-Bearing Horizons.* The characteristics of aquifers in one part of a coastal-plain area often can be used as a guide to the character and productive exploitive possibilities of aquifers in another part of the area. The seaward-dipping beds form a structure containing ground water under hydrostatic pressure. The Atlantic and Gulf Coastal Plains in the United States have aquifers of sand or sandstone and, in places, of limestone confined between beds of shale, clayey sandstone, or clayey limestone (fig. 198). These materials are usually excellent water bearers, with a yield approaching that of sand and gravel. These aquifers outcrop in bands roughly paralleling the coast, and along these exposures shallow wells obtain fair yields. Where the sands dip under impervious strata, flowing wells, are obtained by tapping the deep aquifers throughout the coastal lowland. These wells generally have a small yield. Large yields are often obtained from pumped wells. Both flowing and pumped wells reduce the pressure head, and, in aquifers below sea level near the coast, sea water may move landward into the aquifers if the well discharges are too great. The relationship between fresh and salt water in coastal regions is discussed in paragraphs 172–177.

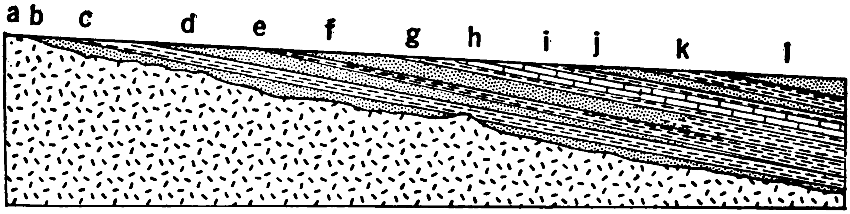



*Figure 198. Diagrammatic cross section of a coastal plain. b, d, f, j, and l are sandy water bearers; c, e, g, i, and k are impervious clayey beds; h is a limestone which is cavernous in upper part.*

## 168. Inland Sedimentary Plains and Basins

*a. Distribution and Nature of Deposits.* Many of the great plains regions of the earth are underlain by thick deposits of consolidated sediments, mostly interbedded shale, sandstone, and limestone of either marine or fresh-water origin. Generally, these beds are nearly horizontal or are inclined very gently. The consolidated sedimentary rocks in the inland plains are covered only by a thin and interrupted blanket of unconsolidated material, in contrast with the coastal plains where the unconsolidated material is deep and contains more aquifers. The overlying unconsolidated material of the inland plains may yield water freely in places, but it generally holds only a small part of the total supply of ground water.

*b. Productivity and Persistency of Water-Bearing Horizons.*

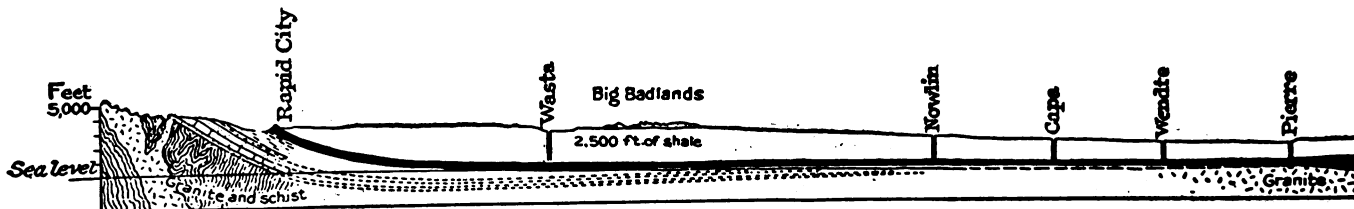
(1) The aquifers in the inland sedimentary plains and basins persist over large areas with little change in water-bearing properties; for example, the Dakota (fig. 199) and St. Peter sandstones of the Missouri-Mississippi basin which persist for hundreds of square miles. Their permeability and their nearly horizontal position make them great reservoirs of ground water. Depths and yields from place to place are usually easy to predict.

(2) The consolidated beds underlying inland plains and basins generally contain aquifers of sandstone and limestone, although in places they are interbedded with considerable thicknesses of shale, dense sandstone, and limestone that yield little or no water. Many of the aquifers contain water under hydrostatic pressure.

(3) Where the aquifers lie within a few hundred feet of the surface they generally yield drinkable water and are readily tapped by wells. Most of the deep aquifers are highly mineralized and in many localities their water is not drinkable. Where thick series of shales or other dense sediments underlie the surface and the deep water is salty, it may be difficult to obtain a satisfactory supply of ground water. In some places, relatively deep aquifers have drinkable water, although it is generally very hard.

## 169. Limestone Areas

*a. Distribution.* Limestone is so widely distributed that no conti-




Courtesy of United States Geological Survey

*Figure 199. The Dakota sandstone aquifer (shown in solid black). Rain in the Black Hills seeps into the sandstone and flows to the east where it is recovered by deep-drilled wells.*

nent is without somewhat extensive surface deposits. A few of the outstanding areas that may be cited are: the famous Karst district of the Adriatic in Yugoslavia; the Causses of central-southern France; the Mammoth Cave region of southern Indiana, Kentucky, and Tennessee; the sinkhole region of Florida; the Carlsbad Cavern region of New Mexico; and the coral islands of the South Pacific.

*b. Productivity and Persistency of Water-Bearing Horizons.*

(1) Limestone is sometimes a good water bearer. If granular or fragmental it may transmit water through interstitial openings. More commonly, it transmits water along bedding planes, joints, and other fractures that have been enlarged by solution. In places, the solution channels may merge to form large irregular cavities and caverns.

(2) Cavernous limestones are among the most productive of all aquifers; for example, in Texas, the Edwards limestone has many wells which yield a thousand to several thousand gallons a minute. The Ocala limestone of central and northern Florida is another example. Large springs may issue where limestone aquifers crop out in the sides of hills or mountains or in valleys. Not all limestones, however, develop solution cavities, since many are too impure and clayey to dissolve readily.

(3) The yield of wells drilled into limestone aquifers is less predictable than that of wells drilled into sandstones, because permeability in limestones is relatively erratic in its distribution. A well which happens to encounter a large solution channel will, in effect, tap an underground stream and may become a heavy producer. Topography and rock structure play an important part in the distribution of solution cavities but the development of the cavities is controlled also by the original composition of the limestone, by the intersection of fracture systems, and by the presence of impervious, insoluble layers. Solution cavities also develop in the purer types of dolomite and marble.

(4) Areas where permeable limestone underlies the surface, such as the distinctive Karst area (par. 31), frequently have few or no surface streams. The surface runoff passes through sinkholes and also percolates directly into the limestone. Streams of considerable size may sink underground, flow for miles through subterranean passages, and eventually reappear

at the surface as great springs. In populated areas, such water may be highly polluted. On plateaus and mountains made up of permeable limestone, the ground water is generally so far below the surface that a ground-water supply may be difficult or impossible to develop. The plateau country of central New Mexico is an example of this condition.

(5) Coral limestone, when not too clayey, has a more or less cellular, sometimes cavernous, structure. Some ancient limestones of high coral content are good aquifers. In the Philip-

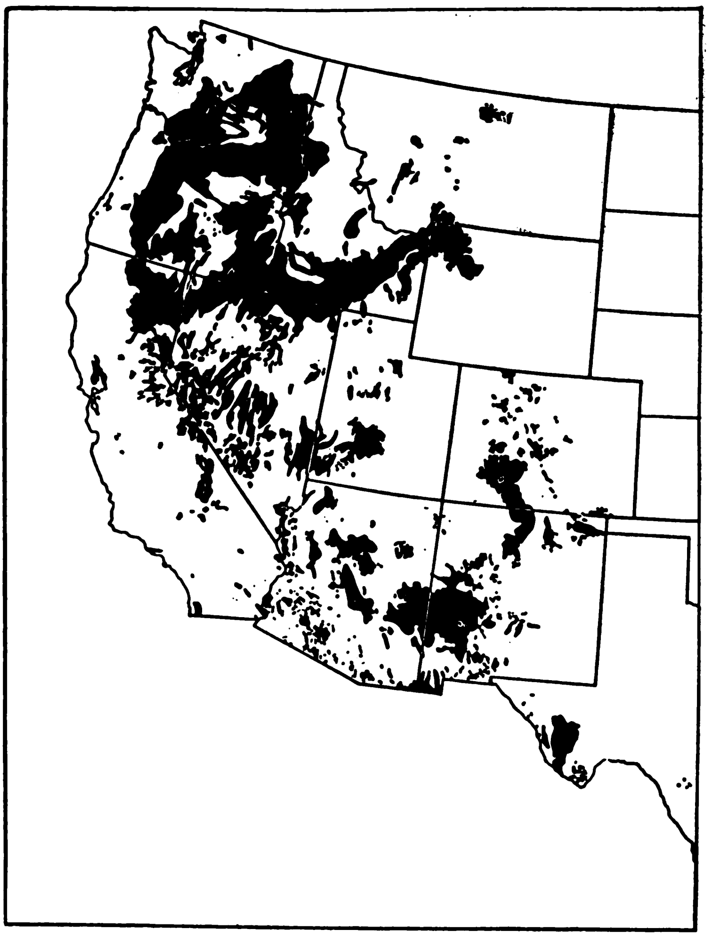


*Figure 200. Map of the lava plateaus and plains in western United States.*

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pines, about 50 percent of the wells drilled in coral limestone have been successful.

## 170. Volcanic Areas

*a. Distribution and Nature of Materials.* Volcanic terrain is of several types. In some regions, extensive sheetlike flows of basalt and andesite form lava plains and plateaus. Large areas of such terrain occur in the western United States, especially in southern Idaho, eastern Washington, and Oregon (fig. 200). In places, beds of volcanic ejecta (cinder beds and tuff) cover extensive areas or are interbedded with lava flows. Many deposits of this nature occur in the Pacific Islands, Mexico, Central America, and Oregon. In some volcanic areas, volcanic cones occur. They are made up of layers of lava or ash, or both.

*b. Productivity and Persistency of Water-Bearing Horizons.*

(1) Basalt and andesite flows, in certain plains and plateaus areas, constitute one of the most important water sources. The water occurs in large joints, tunnels, and vesicules in the rock mass, and between the individual flow-sheets where the overlying bed is unable to mold itself tightly to the slaggy surface of the underlying bed. Where these flows

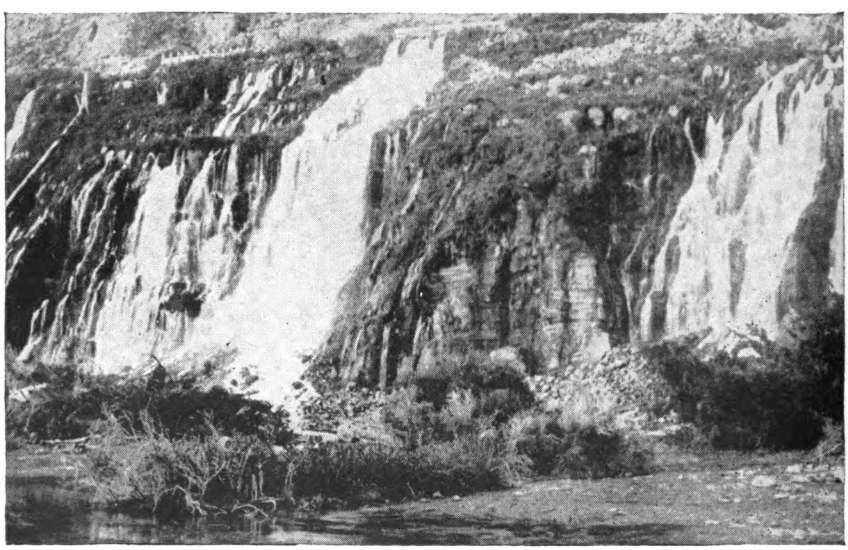


*Figure 201. Springs issuing from basaltic lava, Thousand Springs, Idaho.*

are relatively recent, they are very permeable and most of the precipitation sinks underground, later emerging as springs on the sides and bottoms of valleys (fig. 201). In time, the cracks tend to become filled with clay or become cemented so that old lava rocks behave much like granite and other massive rocks in their ground-water properties.

(2) Low-lying lava plains may have a fairly high water table. Large yields commonly can be obtained from lava beds fairly close to the surface.

(3) Lava plateaus, however, resemble limestone plateaus in that it is difficult to obtain either surface water or ground water from them. Normally the water table is very deep, usually hundreds of feet below the surface. Wells are justified only in exceptional cases, especially since the rock is so hard that drilling is slow and costly. In many regions, lava plateaus have been broken by earth movements so that some blocks have been elevated and others depressed to form basins into which unconsolidated debris has been washed. This alluvium may be the best possible source of water.

(4) Volcanic ejecta are porous enough to yield water in many places, especially beds with cinder-size particles. Most tuff, however, has a dense, siltlike matrix and is a poor water bearer. In places, however, beds of relatively clean sand and gravel that make fair or good aquifers are interbedded with the tuff.

(5) Volcanic cone deposits usually are so permeable that ground water is generally too deep for practicable development by wells. Near the base of the cone, however, springs may emerge and wells may be feasible.

## 171. Crystalline-Rock Areas

*a. Distribution and Nature of Rock.* Granite and allied igneous rocks and metamorphic rocks such as schist and gneiss are commonly grouped together as crystalline rock. They are closely associated in distribution, reaching the surface in most mountains and shields. Their generalized distribution is shown in figure 2.

*b. Productivity and Persistency of Water-Bearing Horizons.*

(1) All crystalline rocks are poor water bearers. Where they are

unweathered, their water-bearing character is determined solely by the number and openness of joints or other fractures. Water-bearing capacity frequently varies greatly within short distances or for different bodies of crystalline rock, and wells even in the same locality may differ considerably in yield. In this respect, wells in cryastalline rock resemble those in limestone and basalt, but as the joints are usually much tighter the average yield will consequently be smaller. Joints tend to be more numerous and open near the surface. Generally, the best yields are obtained above a depth of 100 feet (fig. 202). At considerable depth, these rocks are usually almost devoid of water. Schist is softer than granite and gneiss, and its joints tend to be closed at a shallower depth. It also does not have the well-developed horizontal jointing which is common in granite. Yields of wells in granite, gneiss, and schist range from nothing to as much as 150 gallons per minute in exceptional cases.

(2) Granitic mountains generally have numerous small springs, and, in this respect, are more favorable for ground-water supplies than limestone, quartzite, or slate mountains.

(3) Where crystalline rocks underlie lowlands or low hilly terrain and where they have been deeply weathered, small but reliable supplies can be obtained from shallow wells in the weathered zone. In addition to opening joints, weathering tends to develop small openings between the grains of these rocks, and makes the rocks somewhat pervious. Under favorable conditions, as in the piedmont belt adjoining the coastal plain from Pennsylvania to Georgia, weathering may


*Figure 202. Block diagram showing ground water in joints in crystalline rock.*

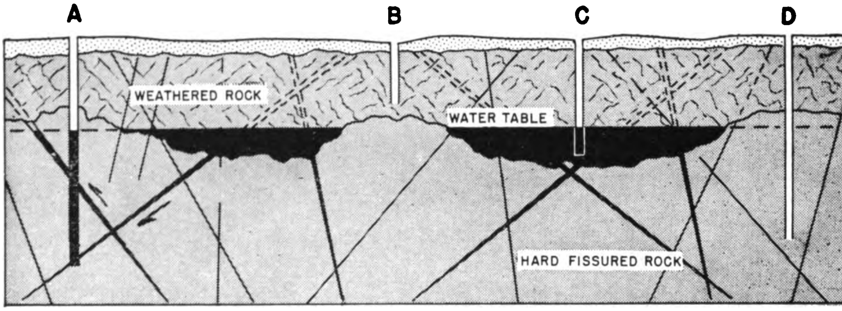



*Figure 203. Relation of wells to weathered rock and to joints. Well A obtains water from fissures. Well B is dry. Well C obtains water from near base of weathered zone. Well D is dry.*

extend to depths of 100 feet or more, the rock changing from thoroughly disintegrated material near the surface to progressively less altered rock as depth increases. Dug and drilled wells 30 to 100 feet deep obtain yields adequate for ordinary domestic and farm needs. For large supplies, several widely spaced wells are necessary, unless long infiltration galleries can be used to collect water from a large area.

(4) In some gently undulating areas, hills or outcrops of hard rock are interspersed with hollows underlain by much softer, more weathered rock. These hollows should be the first areas searched for well sites (fig. 203). The best supplies commonly are obtained in the transition zone between completely decomposed and fresh rock.

*c. Siting of Wells.* Although finding water in crystalline rocks is largely a matter of chance, the odds for success are greater if the well site is selected with reference to the occurrence and dip of outcropping joints. Also, wells should be located in the valleys, even in small depressions, in preference to flat areas or hills. The depressions indicate places where the rock is especially susceptible to erosion and thus where it is likely to be more highly creviced than the rock beneath hills.

## Section VI. THE PROBLEM OF SALT-WATER INTRUSION

### 172. General

The ground water of coastal areas and islands is always in danger of becoming salty from intrusion of sea water. This is a serious problem,

for salty water is unfit for most human use and water too salty for human consumption usually is injurious to automotive cooling systems, locomotive boilers, and other types of machinery. Contamination by salt water is affected by the width of the zone in which sea water may occur at various distances from the shore and the effect of pumping which causes salt water encroachment.

## 173. Determining Salt Content of Water

The only accurate method of determining the saltiness or degree of contamination is by chemical analysis. The average concentration of dissolved solids in sea water is about 35,000 parts per million (3.5 percent). Most of the salts are chlorides.

## 174. Relationship Between Salt Water and Fresh Water

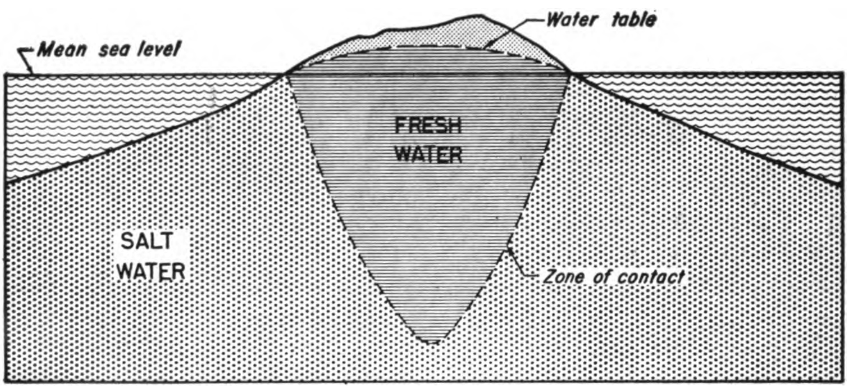
When both salt water and fresh water are present in sediments, the fresh water tends to float on the salt water. The position of contact between the two is determined by the head of the fresh water above sea level and by the relatively greater specific gravity of the salt water. Using the average specific gravity of salt water (1.025), each foot of fresh water between sea level and the water table indicates approximately 40 feet of fresh water below sea level in homogeneous material. This condition is best exhibited by small islands and peninsulas composed of permeable sands completely surrounded and underlain by salt water. The hydrostatic head of the fresh water and the resistance of the pores in the sand prevent the salt water from entering the middle zone and mixing with the fresh water. The zone of diffusion (zone of contact) between fresh water and salt water is narrow (less than 100 feet wide) unless affected by heavy pumping. Along coasts which have alternating beds of pervious and impervious materials, the contacts between salt water and fresh water in the various pervious strata depend upon the hydrostatic pressures of fresh water in each.

## 175. Effect of Pumping

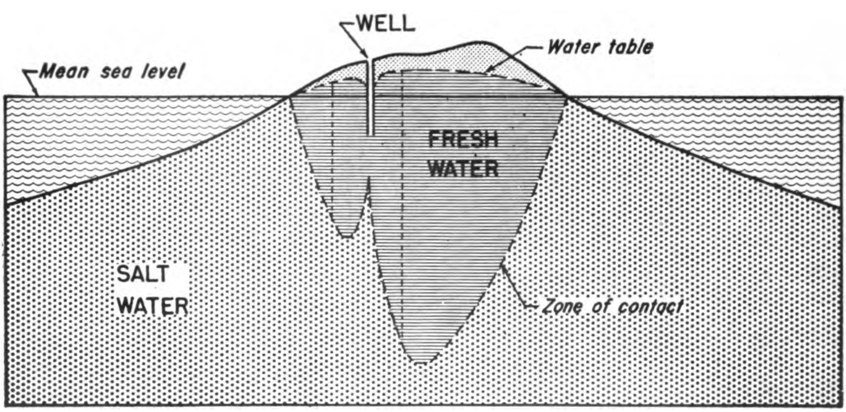
*a.* The amount of fresh water that can be pumped without intrusion of salt water depends on local conditions, type of well, rate of pumping, and the rate of recharge of the sand by fresh water. Any decrease in the head of fresh water, either by pumping or by decrease in rainfall,

allows a rise in the level of the salt water. The "cone of depression" (draw-down) produced in the fresh-water level around a well allows a corresponding rise in the underlying salt water. Pumping of any one well should be restricted according to draw-down, for salt water will enter the well if draw-down is maintained substantially below sea level for extended periods. The pumping rate should not exceed the rate of recharge.

*b.* In a sand island (fig. 204), pumping has a very serious effect on the line of contact between salt water and fresh water. As the head of fresh water is lowered by pumping, the salt water rises in a




① WHEN NOT DISTURBED BY PUMPING




② WHEN DISTURBED BY PUMPING

*Figure 204. Effect of pumping water from wells in sand exposed to salt water contamination in an island composed of sand.*

point or peak beneath the well. This point might be called a salt-water point of elevation. If it rises to the bottom of the well casing, salt water is pumped.

*c.* In an artesian sand (fig. 205), pumping a well has much less

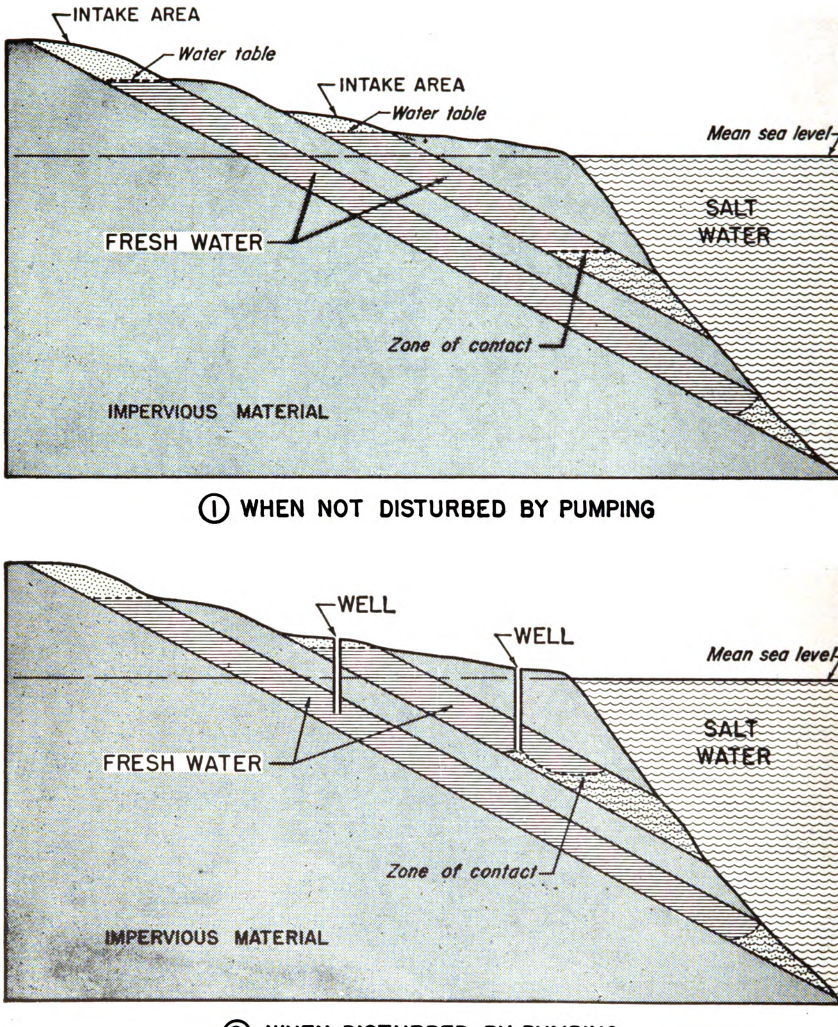



*Figure 205. Effect of pumping water from wells in sand exposed to salt water contamination on the coast of a large land area where artesian sands are confined between impermeable strata.*

effect on the line of contact between salt water and fresh water. If pumping does not exceed the rate of intake in the artesian sand, the line of contact is not changed.

## 176. Problem of Fluctuation of Water Level

The water level of wells in coastal areas may rise and fall with the tides. This affects the position of the salt-water point of elevation at the bottom of the well casing, a condition which may lead to pumping salt water if the casing is too deep into the fresh-water zone. In wells near shore the fluctuations may range from a few inches to several feet. The extent of fluctuation is about the same for wells in fractured-rock formations as for wells in pervious sand.

## 177. Evaluation of Coastal Features as Sources of Water Supply

*a. Tidal Marshes.* Tidal marshes are poor sites for wells because the land surface is unfavorable and the water usually is salty both in the marsh and in the rock formations beneath it. The saltiness of the marsh usually is less than that of the ground water, especially in tidal marshes along river mouths where fresh water is discharged continually.

*b. Bars and Spits.* Most bars and spits are unfavorable locations for wells because the ground water in them is somewhat salty. The sand composing such features is extremely porous, and high waves carry salt water over large parts of small bars, saturating them with the sea water.

*c. Barrier Beaches.* Small barrier beaches are unfavorable for siting of wells. Large barrier beaches, such as that of the western Gulf Coast, have enough area to maintain shallow fresh-water wells.

*d. Islands and Peninsulas.*

(1) A small sandy island or narrow peninsula, where the area is measured in acres, generally has a body of fresh water near the surface. Shallow wells can be either dug or driven. In developing a water supply under these conditions, it is advisable to sink enough wells to yield about twice the required amount. Since the withdrawal of 1 foot of fresh water will cause the level of contact between the salt-water and fresh-water bodies to move upward 40 feet, heavy pumping in one well will quickly deplete the supply of fresh water, especially when the reservoir is limited.

(2) Along the shores of large islands or peninsulas which have

a permanent water table, fresh water occurs to the edge of the high-water line of the tides. On sandy beaches, fresh water may seep from the beach sand at low tide.

## Section VII. AIDS IN FINDING A GROUND-WATER SUPPLY

### 178. Special Reports on Specific Areas

A valuable source of information on general geology and ground water in foreign areas of military operations is a series of Terrain Intelligence Folios prepared by the Intelligence Branch, Corps of Engineers, in cooperation with the U. S. Geological Survey. These folios contain data on resources, industries, and engineering problems of the countries, regions, or islands covered. Folios numbered 1 through 176, prepared during and after World War II, include islands of the western Pacific and bordering parts of the Asiatic mainland, northern Africa, and southern Europe. These folios include maps of topography, geology, ground-water provinces, and tables of information on water supplies of all important cities and towns. Terrain Intelligence Folios are distributed to engineer headquarters in overseas theaters of command and to headquarters, army engineer commands in the various field armies. If folios are not available from these sources, information concerning distribution can be obtained by writing Office, Chief of Engineers, Department of the Army, Intelligence Division, Washington 25, D. C.

### 179. Climatic Considerations

The engineer in the field should first consider the way in which the climate governs the general availability of ground water. If the climate is arid, good aquifers generally will be more spottily distributed than they are in humid climates, and in many places, water will be farther below the surface. If the climate is extremely arid, supplies of both surface water and ground water are likely to be limited. Large ground-water supplies are apt to be obtained only where geologic conditions are exceptionally favorable, necessitating a knowledge of geology in order to take full advantage of all favorable factors. If the climate is humid, ground water may not be needed, as surface-water sources may be accessible and of good quality.

## 180. Cultural Considerations

*a.* In many countries, settlement patterns are determined partly by ground-water supply. People settled first along year-round streams and around springs; then they moved into intervening areas where ground water could be tapped by wells. In densely populated regions, the shallow aquifers almost always have been thoroughly explored by means of existing wells. Although these wells usually have only small yields, some may be adequate sources for military supplies. New wells can be developed to increase the supply of water. Information must be obtained on the position of these aquifers, depth to water, and yield, and it must be considered in connection with the general geology and topography.

*b.* In sparsely settled regions, existing development of ground-water supplies is usually too limited to give many clues that will help in locating new wells. More reliance must be placed on interpreting the ground-water possibilities from geology and topography.

## 181. Geologic and Topographic Considerations

*a.* The best available geologic and topographic maps and water-supply or ground-water maps and reports all should be examined together. Unless the maps give very detailed and specific information, ground study of features will be necessary.

*b.* If the preliminary examination shows that the area is underlain entirely by great depths of impermeable or nearly impermeable rock, such as granite, schist, or a thick series of shale beds, the chance of locating wells with satisfactory yield is too slight to be considered. On the other hand, a river plain underlain by highly permeable gravel and sand may be present, and a well sunk in it at any location would probably develop abundant water at shallow depth. Here the chances of finding ground water will be so good and a supply will be so easy to develop that well sources can be considered for a relatively early phase in field operations. Development of an area where good aquifers are likely to be very irregularly or locally distributed will require more detailed geologic study and test drilling. This extra work is justified only for base supplies or if surface water is very deficient.

*c.* Paragraphs 159–171 discuss the ground-water possibilities of the important types of terrain.

*Table VIII. Principal species of plants which indicate presence of ground water in the western United States.*

| Species | Depth of ground water | Chemical quality of ground water |
|---|---|---|
| Several species of rushes, sedges, and cattails. | At surface or within a few feet. | Generally good, but not invariably. |
| Giant reed grass | At surface or probably within 8 feet. | Generally good, but not invariably. |
| Wild cane | From very near surface to 10 feet or more. | Generally good, but not invariably. |
| Giant wild rye | From very near surface to 12 feet or more. | Generally good, but not invariably. |
| Salt grass | From very near surface to 10 feet or more. | Good to very bad. |
| Pickleweed | Generally within a few feet, but locally may be as much as 20 feet or more below surface. | Generally highly mineralized immediately under the water table, but deeper water possibly a little better. |
| Arrow weed | At surface to possibly 25 feet (heavy growth usually indicates water within 5 to 10 feet of surface). | Generally good, but not invariably. |
| Palm trees | Within a few feet of the surface. | Potable water generally can be found in vicinity of healthy palms but locally may be very bad. |
| Willow trees, several species. | From surface to 12 feet or more. | Generally good. |
| Alkali sacaton | From less than 5 feet to 25 feet, and in places much more; more luxuriant where depth to water table is 5 to 15 feet. | Good to very bad. |
| Rabbit brush | Luxuriant growth indicates water table at 8 to 15 feet (locally as shallow as 2 feet). | |
| Greasewood | From 3 feet or less to 40 feet or more. Abundant and luxuriant where depth is between 10 to 20 feet. | Doubtful; usually appreciably mineralized but drinkable. |

*Table VIII. Principal species of plants which indicate presence of ground water in the western United States*—Continued.

| Species | Depth of ground water | Chemical quality of ground water |
|---|---|---|
| Mesquite | From less than 10 feet to 50 feet or more. | Generally good, but not invariably. |
| Cottonwood trees | Abundant ground water generally within 20 feet. | Generally good. |
| Desert willows | Generally indicates shallow ground water, but locally water table may be at 50 feet or more. | |
| Elderberry shrubs and small trees. | Generally within 10 feet of the surface. | |
| Alfalfa | From 15 to 60 feet; luxuriant growth where water is within 15 feet. | |

## 182. Botanical Considerations

*a. General.* Some species of plants, known as *phreatophytes,* reach water near or below the water table, in contrast to the majority of plants that get their water from soil moisture above the water table. These are the plants that should be looked for, as they indicate that ground water is close to the surface. In arid regions, the ground-water plants contrast sharply with other desert plants that do not obtain water from the water table. In regions with progressively greater humidity, plants depend less and less on the water table, and obtain their moisture from the soil above the water table. Consequently, the presence of certain plants may not necessarily be indicative of the presence of a water table at a certain depth. Even in humid regions, however, useful guides to shallow ground water may be found by observing the plant communities that grow typically where the water table is close to the surface. It should be noted, however, that ground-water plants sometimes obtain their water from a perched water table and, in this event, the ground-water supply may be relatively small.

*b. Desert Plants That Tap Ground Water.* With experience, observation of plants in arid regions will give a good idea of the depth to water. The important plants which are ground-water indicators in the arid western part of the United States are listed below and in table VIII. In other regions of the earth, the critical species differ, but an effort to determine their types and typical habitat with respect

to the water table will repay a water-supply engineer, particularly in arid regions.

(1) *Rushes, sedges, and cattails* commonly grow where surface water is visible in swamps or pools or where the water table is near the surface. Generally they cannot survive dry periods.

(2) *Reeds and cane* occur along streams and ponds and where ground water is near the surface. The common reed grass *Phragmites* has tall, jointed stalks sometimes 10 feet high, with green leaves at the tops.

(3) *Giant wild rye,* a coarse tufted grass 6 to 8 feet high, and other species occur in rich soils where ground water is near the surface and also where rainfall is abundant. They can use either ground water or soil moisture. In subhumid regions they may grow without relation to the permanent water table.

(4) *Salt grass,* is a creeping rhizomatous grass 6 to 12 inches which grows on the margins of salt flats in saline soils. It is one of the most reliable and useful of the shallow ground-water indicators (fig. 206).

(5) *Pickleweed* is a shrubby plant less than 2 feet high with cylindrical jointed leafless branches. It grows on salt flats in soil which has between 1 and 2 percent salt content. Pickleweed usually indicates permanent moisture at 1 to 4 feet below the surface.

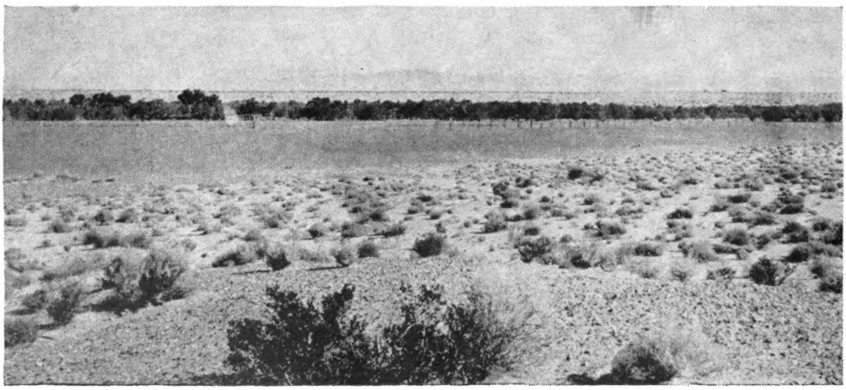


*Figure 206. Desert plants which indicate depth to ground water, Mojave River Valley, California. Brush indicates water at considerable depth. Salt grass on flat beyond brush indicates ground water at a shallower depth.*

(6) *Arrow weed* is a rank smelling purplish shrub with long straight stems which forms thickets on moist saline soil.

(7) *Palm trees* are reliable ground-water indicators especially in desert areas of Africa and Asia Minor. In the hot, arid region of southwestern California, occurrence of palms invariably indicates a spring or ground water within a few feet of the surface. Because palms grow to heights of 50 feet or more they can be seen for miles as sign posts of shallow ground water.

(8) *Willow trees* use ground water either at the surface or near it. They are common along streams in any region, arid or subhumid.

(9) *Alkali sacaton* is a coarse perennial drop-seed bunch grass 1 to 3 feet high found on moist saline soils and along drainages throughout the southwest.

(10) *Rabbit brush,* in the deserts of Nevada, Utah, and California, is a conspicuous ground-water indicator. It is a shrub with whiplike branches, gray-green leaves, and, in late summer, yellow blossoms resembling those of goldenrod. Rabbit brush generally indicates ground water at a depth of less than 15 feet. However, small individuals of this species or related species are widespread on uplands where the water table is very deep.

(11) *Greasewood* is one of the best and most conspicuous indicators of ground water in all of the northern desert areas of the United States. It should not be confused with the creosote bush which usually does not tap ground water. Greasewood grows in bushes 3 to 6 feet high, and has a deep, blue-green color which makes a vivid contrast to the sages. It can send its taproots to depths of 30 to 40 feet to tap ground water.

(12) *Mesquite* can send its taproot along moist belts to a depth of about 50 feet to tap ground water, but it also can adapt itself to use soil moisture in lowland areas. It occurs widely in southwestern United States and in the southern half of South America. In general, the smaller mesquite indicates a greater depth ground water is reached.

(13) *Cottonwood trees* are reliable indicators of ground water in the arid parts of western United States and other countries.

*Figure 207. Grove of cottonwood trees indicating an area of shallow ground water. Near Salton Sea, California.*

The desert varieties commonly occur where the water table is reached 20 feet or less below the surface (fig. 207).

(14) *Desert willows* are small trees with large purple flowers which grow along streams in the southwestern United States. They are not a species of the willow trees in (8) above. Desert willows use either soil moisture or ground water at depths of 50 feet. They are not reliable as ground-water indicators.

(15) *Elderberry* shrubs and small trees grow along streams and drainages. Some varieties have more or less evergreen leaves. The *Mexican elderberry* characterized by a compact round-topped crown attains a height up to 30 feet with a trunk 18 inches in diameter.

(16) *Alfalfa* grows best where ample water is available, but it can send roots down 60 feet or more to use ground water. It does not have abundant foliage where the depth down to the water table is more than 15 feet, but it is a good ground-

water indicator. It grows wild in Persia, central and western Asia, and northern Africa.

(17) *Forest trees.* In humid areas or in the more humid mountain parts of arid areas, it is impossible to distinguish definitely between the forest trees that habitually use ground water and those that do not, but it is certain that some species depend much more on ground water than others. Several species of birch, sycamore, alder, willow, and live oak are examples of trees which, in the forests of the East and South, show obvious preference for lowland tracts where they can utilize shallow ground water, although they may not be confined to such tracts. These species are not all equally dependent on ground water. For example, some species of birch show more preference for shallow-water areas than do others, and the different species of oak range from those that depend almost wholly on ground water to those that are markedly independent of the water table.

*c. Desert Plants That Do Not Commonly Tap Ground Water.* Some of the common desert plants that do not indicate ground water are cacti, big sagebrush, creosote bush, and most of the yuccas. They occur in large areas of arid western United States and some of them occur in other continents. They can live by using extremely small quantities of moisture derived from the soil, and many of them remain in a dormant condition for months.

*d. Identification of Ground-Water Plants on Air Photographs.*

(1) In arid regions, ground-water indicator plants stand out strikingly on air photographs, being more luxuriant and conspicuous than the other desert plants. Springs and seepages can be spotted easily. Even in humid regions some of these plants are easy to identify on aerial photographs; for instance, sago palms, which indicate copious amounts of fresh water near the surface (fig. 208).

(2) All ground-water plants transpire large amounts of water. It is possible to get a general idea of the minimum quantity of shallow ground water available in an area where these plants are growing, by noting their extent and density and the rate at which they transpire water. Data have been published on the transpiration rates for several species of ground-water plants. On Okinawa, for example, numerous limestone springs not situated along year-round streams supply water

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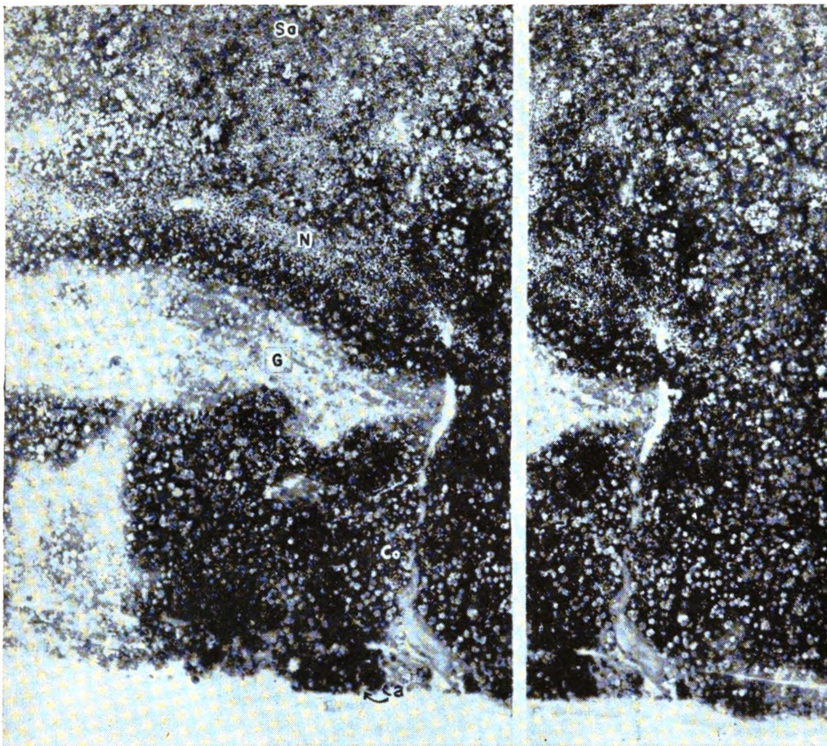


*Figure 208. Aerial view (stereoscopic pair) of tropical vegetation indicating ground-water conditions on a low coastal plain. Ca, sandy beach with casaurina; Co, forest with scattered coco palms, indicating dry land; G, grassy area, considerable depth to ground water; N, nipa palms, indicating brackish-water swamp; Sa, sago forest indicating fresh-water swamp. Northern New Guinea.*

for the irrigation of paddy fields. The yield from the springs was estimated from the area of the paddy fields and the nature of the plants being cultivated therein.

## Section VIII. GROUND-WATER FIELD RECONNAISSANCE

### 183. Pre-Reconnaissance Requirements

Before attempting a ground-water reconnaissance of an area or before sinking wells, the military engineer should study any available reports dealing with the water supply of an area. Intelligence reports

usually give the general availability of ground water, the places where it can be most readily developed, the extent of development, and the quality of the water. From these reports he can also learn something of the geology, terrain, and climate of the area. The possession of this information will help him to expedite his field observations.

## 184. Types of Traverses Used in Reconnaissance

*a.* The types of traverses which may be required for a reconnaissance of ground-water possibilities are many and varied, depending on the base maps available, the scope or size of the water-development program, and the accessibility of the area. If roads are well distributed, most of the reconnaissance can be made with a light truck or automobile. If the topography is rugged and roads are lacking, the field work may be done on foot or by horse.

*b.* The routes of detailed traverses should be planned to allow all outcrops of possible water-bearing formations to be studied and their relations to topogrophy and intake areas understood. This can be accomplished by a preliminary inspection of the entire area to be investigated. Routes of surveys, extent of outcrops, and trends of ridges, valleys, and bluffs should be determined by compass or planetable traverse. Relative elevations of important points should be determined by hand level or by an altimeter, especially if a topographic map is not available.

## 185. Base Maps for Reconnaissance

*a.* Before locating sites for wells, the important ground-water features should be investigated in detail and plotted accurately on a base map. For most ground-water surveys, the best type of base map is a topographic map with a scale of not less than 1:63,360, similar to the U. S. Geological Survey quadrangle maps, 1:62,500. When the positions of outcrops, the extent of each rock formation at the land surface, and the borders of alluvial formations are plotted on such a map, their relations to topography are immediately evident.

*b.* Aerial photographs, aerial mosaics, and photomaps are good base maps, but they show elevations less positively than topograpic maps. Photomaps are adequate base maps for most geologic work, and the commonly used scale of 1:20,000 is satisfactory in most areas. The military grid can be used for reference to important points of the survey and for reporting well locations.

## 186. Data To Be Recorded

*a. Outcrops.*

(1) In prospecting for ground water, special study should be given outcrops of the common types of water-bearing rock such as sands, sandstone, gravels, fractured and cavernous limestones, porous basalts, and highly fractured formations of any type.

(2) Before making a detailed study, each outcrop should be observed as a whole. Its extent and its general relationship to its surroundings should be determined and plotted on the base map. Then a detailed study of the outcrop should be made. At least the following points should be noted and recorded:

(*a*) Type or types of rock.
(*b*) Stratification (including thickness and dip of all beds).
(*c*) Porosity and probable water-bearing characteristics.
(*d*) Grain size and degree of sorting.
(*e*) Contacts between formations.
(*f*) Possible unconformities.
(*g*) Degree of cementation.
(*h*) Possible cavernous conditions.
(*i*) Joint systems (including spacing, amount of open space, arrangement, and dip).

(3) All outcrops in the area under investigation should be covered on foot as far as possible. Any seeps or zones of moisture should be studied and traced, because the rock from which they issue probably will yield water at other places.

*b. Existing Wells and Springs.* Possibly the most important item in a ground-water survey is a complete tabulation of information on existing wells and springs. Location of all wells and springs should be plotted on the base map. Natives of the area, especially owners and users of the wells, should be consulted whenever possible, and the drilling records of drillers who operate in or near the area should be obtained. The following items should be tabulated for each well, so far as possible:

(*a*) Type of well (drilled, bored, dug, or other).
(*b*) Kind of casing (and screen if used).
(*c*) Total depth.
(*d*) Depth at which water first was found.

(*e*) Depth of all water zones in well.
(*f*) Present static level of water.
(*g*) Amount of water produced.
(*h*) Draw-down of water when pumped.
(*i*) Complete log of the well.
(*j*) Date constructed.
(*k*) Elevations, or relative height, at the curb.

## 187. Utilization of Data

*a. Prediction of Logs.*

(1) The prediction of the log as to total depth and depth to water in a proposed well is important in military operations because these characteristics determine the time involved, the amount of casing needed, and the type pump required.

(2) All the information assembled in the ground-water reconnaissance must be used in predicting the log. If the well is to be at the same elevation as an existing well for which the log is known, it should have a similar log and water-producing capacity. If no local well records are available, and only a thin rock section is exposed in the surrounding area, or if the region is undeveloped, only an indefinite prediction can be made. For such wells, test-drilling may be necessary.

*b. Siting of Wells.* The final decision on locating a new well is based on all the information obtained by the reconnaissance survey. If more than one prospect exists in the area investigated, paragraphs 159–171 will facilitate selecting the most desirable among those available. In addition, the following precautions should be taken in any well site selected:

(1) Upland sites for shallow wells should not be nearer than 250 yards to high bluffs or deep valleys, because water usually percolates more rapidly from formations along breaks in the topography.

(2) Surface-water seepage and contamination can be minimized by locating the well on well-drained sites.

(3) Isolated high points or hills should be avoided because of the deeper drilling required.

*c. Reports.* Upon completion of a ground-water study and develop-

ment project, a complete report of the operation should be prepared. This report can be used as a guide in later water projects in the vicinity or in adjacent areas. The report should contain all details of the reconnaissance study, the test-drilling, final drilling, testing of wells, and a copy of the field map used in the work.

# APPENDIX I

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